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STUDY OF THE APPLICATION OF AUTOMATION TO COMPOSITES MANUFACTURE

May 1989

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ABSTRACT

Several alternative manufacturing technologies have been developed to replace current labor intensive manual fabrication methods for advanced thermoset composites. The objective of this study was to evaluate the effect of direct labor savings, quality improvements and process flexibility on manufacturing cost, and to identify desirable characteristics for new equipment. To estimate the cost benefits of replacing manual laborers with equipment, an economic model based on data from the literature and industry was developed. Knowledge of process physics and human error models was used to assess overall quality and estimate related costs such as rework, inspection and scrap. To evaluate process flexibility, system simulation techniques were used to analyze the tradeoffs between response time, work-in-progress inventory, equipment utilization and manufacturing cost.

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1. INTRODUCTION

1.1 Motivation

The high strength and stiffness to weight ratios of advanced composites have led to performance improvements in aircraft and other aerospace vehicles. The high material and manufacturing costs of these composites, however, has limited their use to applications in which performance is critical. Current manufacturing methods are very labor intensive and the end product is subject to the skill of the laborer. To reduce costs and produce more consistent quality parts, several different automated methods of fabrication have been developed.

Methods of producing advanced composites can be classified into two groups: (1) those that use prepreg - a fabric of fibers embedded in a partially cured resin and (2) those which use raw materials - fibers and wet resin. To produce a part by autoclave cure prepreg methods, multiple layers of prepreg are cut and layup on a tool surface, a vacuum is applied and the part is placed in an autoclave to cure for several hours. Automated cutting systems, prepreg transfer robots and prepreg tape layup systems are used to automate parts of this process. Wet methods include pultrusion, filament winding and resin transfer molding. Although manufacturing costs are lower for wet processes, the prepreg methods may offer higher quality and more process flexibility.

Traditionally, the acquisition of equipment has been justified in terms of direct labor savings. Since the cost of labor input exceeds 10% of sales in only a few industries [1], slight improvements in labor productivity result in a small increase in profit for the firm. Higher quality, reliable delivery, shorter lead times and flexible capacity, however, are important strategic advantages which can lead to a higher market share and a more substantial increase in profit for the firm. Since labor costs tend to represent less and less of the overall cost of products in the high technology industries, justification methods for automation equipment that are largely based on direct labor cost reduction have become increasingly less acceptable. In fact, Kaplan [2] maintains that today's accounting systems undermine production by not including nonfinancial performance measures such as quality, inventory, productivity, innovation and workforce morale.

Process flexibility has become an important issue in today's manufacturing environment. This is especially true in the aerospace industrial in which production volumes and lot sizes are low. In many nonaerospace industries, since the half life of many products has decreased to the point that 50% of sales occur within the first three years [3], the ability to accommodate design changes is important. Many companies are, therefore, choosing to compete by introducing a constant stream of new high quality products rather than efficiently producing mature products. For this market, quality, high performance, timely delivery and product customization are the keys to success. Although many different justification techniques have been developed to evaluate advanced manufacturing technologies, the majority of the methods are very qualitative. It is often very difficult to quantify the indirect costs and benefits.

One of the objectives of this study was to develop a quantitative method to evaluate the benefits of advanced composite fabrication technologies. This method was used to determine the effect of direct labor savings, quality improvements and process flexibility on manufacturing cost of current technologies. This analysis was then used to suggest necessary areas of improvement and identify desirable characteristics for new equipment.

1.2 Previous Work

Sullivan [4] and Meredith et al. [5,6,7] summarize many of the available justification techniques ranging from simple discounted cash flow analysis to more abstract techniques which attempt to account for indirect benefits. Meredith identifies three levels of integration, shown in Figure 1.1, and examines the appropriateness of different justification techniques for each level of integration. The levels of integration include (1) stand-alone equipment such as robots or NC equipment, (2) cells or islands such as group technology lines and flexible manufacturing systems and (3) computer integrated manufacturing systems in which design, planning, materials handling, manufacturing and support systems are all linked together.

For the first level, common economic justification techniques are the most appropriate. These well known approaches include return on investment (ROI), payback analysis, net present value (NPV) and discounted cash flows (DCF). Generally one wants to replace existing equipment to achieve better quality, efficiency, speed or capacity. It is important to include decreased inspections, lower levels of inventories, floor space savings, increased safety, reduced rework and scrap, less downtime and changes in setup times in the cost analysis.

For cells, analytic methods such as portfolio analysis and risk analysis which evaluate less tangible benefits are suggested. Portfolio techniques [8] evaluate methods by comparing weighted sums of ratings of several qualitative criteria one of which may be economic. Risk analysis [9,10,11,12] relies on simulation of probabilistic factors, such as labor rates, equipment costs and capacities, to statistically describe outcomes such as profits, lead times, ROI, or market share. For the third level, less formal strategic techniques [13] are used to evaluate technical importance, business objectives, competitive advantage and research and development benefits.

1.3 Approach

Although the basic philosophy of these techniques can be applied to this problem, the majority of the techniques available in the literature are very qualitative and rely on subjective ratings to measure quality and process flexibility. One objective of this study was to develop more quantitative measures to justify automated technologies for advanced thermoset composite fabrication. The economic benefits of standalone equipment replacement and less tangible benefits such as quality improvements and process flexibility were examined. To evaluate wet processes, which are standalone systems, the economic model and quality variations were considered. For the prepreg

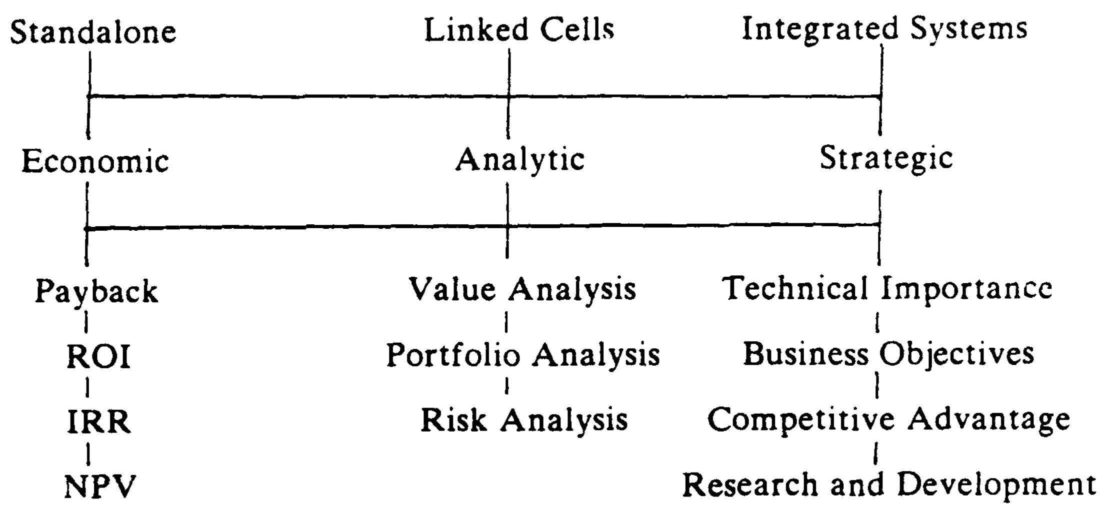


Figure 1.1 Justification Techniques

methods, which can be used in a more integrated system, process flexibility was considered as well as economic payback and quality.

Although quality is a difficult criteria to quantify, it is particularly important for the comparison of wet processes and prepreg layup techniques. There are three quality related problems - (1) human error, (2) process limitations which restrict the ability to produce a part of satisfactory quality and (3) process variability which may lead to inconsistent quality. Human error models were used to quantify quality differences between manual and machine assisted layup methods. Knowledge of process physics was used to evaluate process limitations and characterize the effect of variations in input parameters on quality characteristics. The economic analysis was adjusted to account for quality differences.

The relative benefits of process flexibility will depend on the manufacturing strategy of the firm. Although process flexibility may result in higher manufacturing cost, faster response time, larger product mix and shorter lead times may increase market share or the selling price of the product and increase revenues of the firm. A simulation program which measures the system response to randomly arriving jobs and equipment downtime was developed to evaluate response time, throughput time and equipment utilization. The tradeoffs between equipment utilization, work-in-progress inventory costs and manufacturing cost were investigated for varying production volumes.

The optimal manufacturing system for a given firm will be a function of production volume, lot sizes, quality requirements and the competitive strategy of the firm. In this study, current technologies were evaluated and desirable characteristics of new equipment were identified. The next section discusses an economic model which evaluates the manufacturing cost for each process. The third section discusses economic issues including direct cost comparisons, sensitivity analysis and indirect costs. In the fourth section, system issues including the tradeoffs between response time and manufacturing cost are discussed. Quality issues are presented in the fifth section. The sixth section includes conclusions and recommendation for future processes.

2. ECONOMIC MODEL

2.1 Introduction

Generally, the first step in justifying the acquisition of a manufacturing technology is an economic comparison with the present system. Traditionally, it has been assumed that the manufacturing cost has three components: (1) direct material, (2) direct labor and (3) manufacturing overhead. Overhead consists of indirect labor or material, depreciation of factory machinery and buildings, and factory administration and supervision. These expenses are accumulated into a single burden rate which is multiplied by direct labor hours to determine the overhead cost component.

With the advent of more complicated and expensive manufacturing systems, this type of accounting does not provide a fair evaluation of competing approaches [14]. Due to the higher depreciation costs of automated systems, overhead frequently represents the largest component of the manufacturing cost and is not necessarily proportional to the direct labor hours. This is particularly important when manufacturing methods with different levels of automation are compared. A more expensive system may consume more overhead resources, but appear more cost effective since it may use less direct labor hours. Overburdened labor rates may give the impression that the elimination of people is cost effective despite large capital investment in equipment.

In this study, a modified approach is taken to compare manufacturing technologies. Equipment depreciation as well as material, labor and tooling are considered direct costs. These components are the major focus of the cost analysis which compares the cost of manufacturing a part by hand layup of prepreg broadcloth to several alternative methods. Critical indirect costs which are affected by the new technology are also considered. In the next subsection, the alternative manufacturing technologies are described. This is followed by a subsection on the direct cost model including equipment depreciation, labor, material and tooling costs. Indirect costs are discussed in the final subsection.

2.2 Description of Alternative Manufacturing Methods

The alternatives selected for this study included automated prepreg cutting with manual layup, automated prepreg cutting with robotic ply transfer, automated tape layup, pultrusion, filament winding and resin transfer molding. Each of these manufacturing methods varies in the degree of automation, the investment in equipment and the geometry of parts that can be produced. These methods, which are described in [15], were selected on the assumption that they are representative of currently available and proposed alternative methods.

2.2.1 Manual Production

Although hand layup is a very labor intensive, tedious procedure, it is the most common method used today to produce advanced composites. During hand layup, layers of prepreg material are successively placed on a cure tool until the desired part thickness is obtained. After the placement of each ply, a tool is used to remove trapped air and the protective backing paper is removed. To ensure proper adhesion of each ply to the preceding one and eliminate any remaining trapped air, the plies are compacted by application of pressure to a stack of plies enclosed in a vacuum bag after every third ply. When very thick plies are being manufactured, a heated compaction, referred to as debulking, may be necessary every 6 to 10 plies [16].

When the layup is complete, the part is placed in a vacuum bag and cured in an autoclave by simultaneous application of heat and pressure. A bleeder system is generally applied before vacuum bagging to absorb excess resin and permit the escape of volatiles. After the cure cycle, the part is removed from the vacuum bag and the tool is cleaned and reused. This labor intensive method can result in process flow time of 16 to 24 hours for a forty foot long shape and fabrication labor costs up to 30 hours per pound [17]. A wide variety of parts, however, can be produced by hand layup since part contour and intricacy is not limited.

2.2.2 Automated Ply Cutting with Manual layup

Today, the manual cutting of uncured prepreg is frequently replaced by more automated methods such as reciprocating knife, laser or water jet systems. These systems are generally computer controlled and use nesting algorithms to reduce scrap and waste. In this study, the reciprocating knife was the system chosen for comparison with manual prepreg cutting. This system generally consists of two cutting tables in parallel to reduce cutting head idle time during unloading. After the operator unrolls prepreg material onto the cutting table, a thin plastic film is placed over the material and anchored by a vacuum. Since this film must be removed after cutting, it can present a problem for later integration into a fully automated schemes. Although this system can cut multiple plies of graphite/epoxy, it cannot cut boron/epoxy due to the hard boron filaments.

2.2.3 Transfer Robot with Automated Ply Cutting

Although some companies have implemented automated cutting systems, the transfer of piles from the table to the layup tool is generally performed manually. Robots, however, have been implemented [18] to transfer broadcloth material between the cutting table and the layup tool. The robot is equipped with a slightly contoured vacuum surface which utilizes a rocking motion together with an air pressure differential to pick up and deposit plies. The entire transfer cycle lasts less than a minute per ply. Since there is a limit on the area of the part imposed by the size and weight of the robot head and on part detail due to vacuum grid geometry, this system may not be a practical transfer method for large or detailed components.

2.2.4 Automated Tape layup

Tape layup combines the cutting and layup steps into one process. Numerically controlled tape layup machines, shown schematically in Figure 2.1, generally consist of a gantry on which the dispensing head is mounted which moves above the tool surface. A rotating head dispenses the tape, while

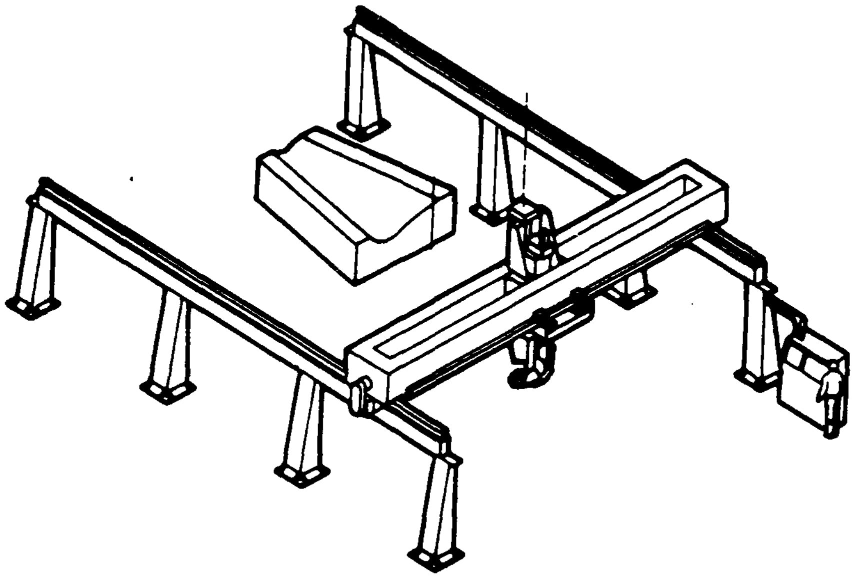


Figure 2.1 Schematic of Tape Layup Equipment [19]

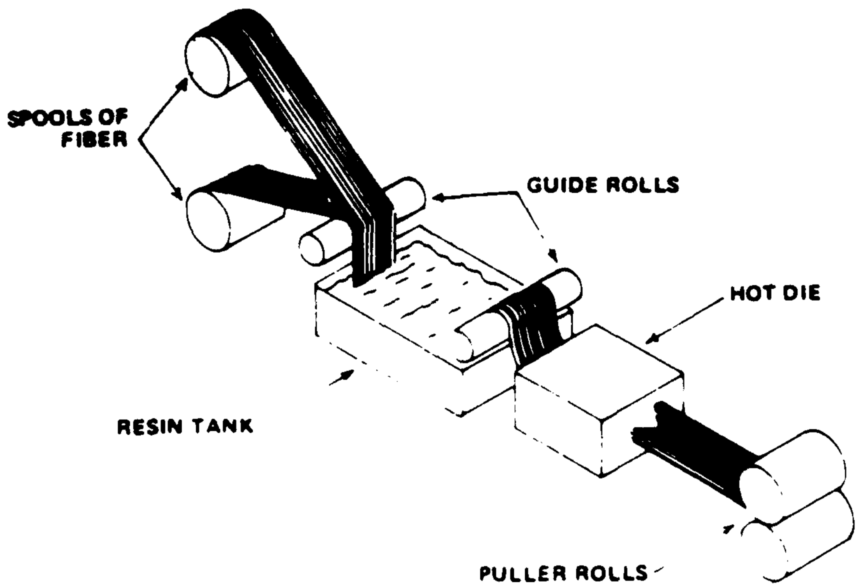


Figure 2.2 Schematic of Pultruder [20]

removing the protective backing, in a predetermined pattern and automatically cuts the tape to the required length and angle at the edge of the part. It is assumed that tape layup eliminates the numerous compaction steps by exerting sufficient pressure as it applies the tapes to the tool surface. The contour of the part is limited.

2.2.5 Pultrusion

Pultrusion, shown schematically in Figure 2.2, is the composite equivalent of metallic extrusion. During this continuous molding process, fibers are pulled from dispensing reels through a resin bath which coats the fibers with a thin film. The stock is then drawn through a heated die to form the desired shape and cure the resin. The cured profile is then cut into the appropriate lengths. Although current pultrusion techniques are very efficient low cost operations, the part geometry is limited to unidirectional fiber orientation and constant cross sections profile. Although the pultrusion of prepreg materials enables the production of multidirectional fiber parts, the material costs can reach one hundred twenty dollars per pound [21], since a higher grade precisely cut prepreg material is necessary.

2.2.6 Filament Winding

The filament winding process, shown schematically in Figure 2.3, consists of wrapping bands of continuous fiber over a mandrel in a single machine controlled operation until the desired part thickness is obtained. There are two principle types of winding; wet winding in which fiber is fed from the spool, through an impregnating resin bath and onto the mandrel, and dry winding in which preimpregnated fiber is fed either through a softening oven and onto the mandrel or directly onto a heated mandrel. Frequently, the part is cured in an autoclave after winding. Filament winding is best suited for cylindrical shapes and there are limitations on the fiber orientation. To produce a flat part, the laminate is slit from the mandrel and placed on a flat tool. In this study, filament winding with both autoclave and oven cure will be considered.

2.2.7 Resin Transfer Molding

RTM has always been viewed as an economic process for moderate production volumes. Although the equipment costs are low, the cycle times are too long for mass production. During the RTM process, shown schematically in Figure 2.4, one or more layers of fiber reinforcement are placed into a mold and held in position by the clamping force of a hydraulic press. Resin is then forced at a controlled pressure or flow rate through the fiber form. The use of shuttle presses improves efficiency by allowing fiber placement and resin impregnation to occur simultaneously. Frequently, three dimensional fiber forms are used to prevent fiber movement. There is a tradeoff between maximum attainable fiber volume fraction and part size.

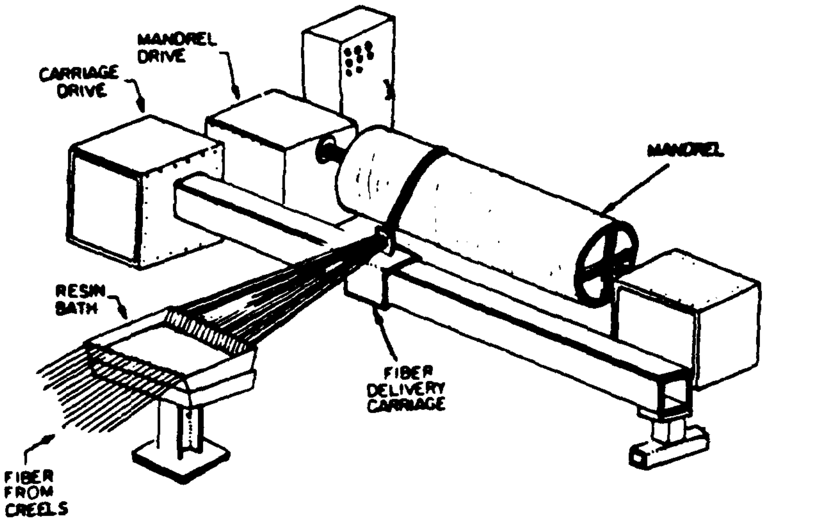


Figure 2.3 Schematic of Filament Winder [9]

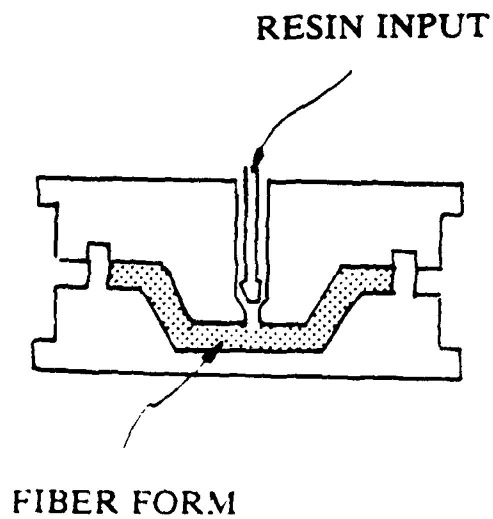


Figure 2.4 Schematic of Resin Transfer Molding

2.3 Direct Costs

The economic model compares the direct cost of manufacturing a flat composite part of variable length, width, thickness and fiber orientation by hand layup to the cost of alternative automated procedures. The analysis is based on the present worth method. The investment capital and operating costs now and in the future are evaluated in terms of their present dollar value. The direct manufacturing cost is given by

$$C = C_E + C_L + C_M + C_T \tag{2.1}$$

where C_E is the equipment depreciation, maintenance and operating cost, C_L is the labor cost, C_M is the material cost and C_T is the tooling cost. The model is based on information in the literature, government reports and design guides and has been compared with industrial experience to validate its accuracy.

2.3.1 Equipment Depreciation

The capital investment in equipment includes the purchasing value of the equipment and any auxiliary equipment and installation costs. The annual cost of maintenance can be estimated as a percentage of the capital investment in equipment. The total equipment cost is given by

$$C_E = (C_d + C_i F_m)/N \tag{2.2}$$

where C_d is the equipment depreciation during the production period, C_i is the capital investment in equipment, N is the annual production volume and F_m is the percentage of equipment capital investment necessary for annual maintenance. The operating power has been neglected.

In this analysis, it is assumed the the equipment follows a straight line depreciation. Assuming no salvage value, the depreciation of a given piece of equipment over the production time is given by

$$C_d = C_i - C_{rl} \tag{2.3}$$

where

$$C_{rl} = C_i (L - T) /L (P/F, i, T)$$

$$(P/F, i, T) = (1 + i)^{-T}$$

where C_{rl} is the value of the remaining useful life, (P/F, i, T) is the present worth factor, i is the interest rate, T is the production period, and L is the useful life of the equipment.

The capital investment in equipment will vary depending on the size, geometry of parts and the materials used, the annual production volume required and the sophistication of the equipment. When the annual production volume exceeds the production volume of the equipment, it is necessary to use multiple machines operating in parallel to produce the specified number of parts. Ideally the production volume should be regulated to maximize machine operation time. Estimates of equipment costs to produce flat medium sized parts are summarized in Table 2.1. These estimates are based on conversations with personnel from the aerospace industry. It is assumed that the annual maintenance is 3% of the capital investment and the equipment is operated three shifts per day and has no salvage value. One operator is necessary to control each piece of equipment. The capacity of the autoclave and oven is 128 parts. The capital investment in equipment is borrowed at 10% interest rate [23] and is depreciated over a eight year period according to IRS guidelines [24].

Table 2.1 Equipment Cost Parameters

Reciprocating knife system	$1,500,000 [25]
Transfer robot	$500,000 [26]
Tape layup machine	$1,500,000 [27]
Filament winder	$275,000 [28]
Pultruder	$150,000 [29]
RTM pumping system	$18,000 [30]
RTM press	$22,500 [31]
Autoclave	$1,200,000 [32]
Oven	$600,000

2.3.2 Labor Costs

Labor costs are based on part cycle time, the learning curve and the degree of skill required. To determine direct labor costs, it is frequently assumed that laborers can be switched from one task to another without any penalty. Therefore, direct labor costs are only incurred during actual cycle time for the part. Since production volumes are low and equipment may be operated below capacity, a more realistic approach is taken in this study. It is assumed that each method requires a task to be completed at each of n workstations. Therefore, manual laborers and operators are hired per shift for a specific workstation and must be paid for idle time. It is assumed, however, that skilled labor expenses are only incurred during actual programming and setup time.

The labor cost is given by

$$C_L = \Big(\sum_{i=1}^{j} N_i\, L_m\, t_y + \sum_{i=1}^{k} (N_i\, L_o\, t_y + s_i\, L_s)\Big)(P/A, i, T)/N \qquad (2.4)$$

where

$$n = j + k$$

$$(P/A, i, T) = (1 - (1 + i)^{-T})/i$$

where j is the number of manually operated workstations, k is the number of automated workstations, N_i is the number of laborers or operators at the ith workstation, L_m, L_o and L_s are the manual, operator and skilled labor rates, t_y is the available working hours in a year and s_i is the setup time for the ith workstation. The tasks performed at each workstation for each process are summarized in Table 2.2.

Table 2.2 Summary of Workstation Tasks

workstation	1	2	3	4
manual	layup	autoclave prep	cure	
automated cutting	cut	layup	autoclave prep	cure
robotic transfer	cut	transfer	autoclave prep	cure
tape layup	tape layup	autoclave prep	cure	
pultrusion	pultrude			
filament winding	wind	autoclave prep	cure	
winding w/oven	wind			
RTM	fiber layup	fill mold		

2.3.2.1 Cycle times

For manual layup, the cutting and layup cycle times are dependent on the part size. To determine the manufacturing time for parts of similar design but different size, power law relationships based on time studies have been developed by Northrop [33]. For a flat graphite part, the time in minutes required for hand layup of N_p plies is dependent on the ply area in square inches, A, by the relationship

$$t_L = 3.0 + N_p .045 A^{.6295} \tag{2.5}$$

where t_L is the time required to unroll the woven material on the layup table, scribe and cut the pattern and layup the material on the curing tool. The additional time required to layup a shaped or contoured part can be quantified using correction factors.

The compaction time in minutes, t_{CP}, is dependent on the surface area of the ply in square inches and the type of vacuum bag. The layup is generally compacted every third ply. For a disposable vacuum bag, the time required to compact is

$$t_{CP} = 1.2 + .105 A^{.6911} \tag{2.6}$$

and the time in minutes for a reusable bag is given by

$$t_{CP} = 1.2 + .0334 A^{.8150} \tag{2.7}$$

Although the compacting time for a reusable bag is lower than that for a disposable bag, the initial investment is higher for reusable bags.

The tool preparation time in minutes which includes cleaning the tool surface, applying release agent, applying and removing the bleeder plies, attaching and detaching the vacuum ports and thermocouple leads and loading and unloading the part is given by the expression

$$t_{AP} = 19.6 + .00762\ A_b + .0012\ A_r + 3.93\ N_f + .0174\ A^{.6711} + .0774\ P_b \tag{2.8}$$

where A_b is the bagging area in square inches, A_r is the area of the resin bleeder plies in square inches, N_f is the number of vacuum fittings and P_b is the perimeter of the bag to be sealed or clamped in inches. Two vacuum fittings are used if the bagging area is greater than 432 square feet. Figure 2.5 compares the hand layup, compaction with a reusable bag and autoclave preparation time for a square part of varying area.

Estimating the cycle times for tape layup and automated prepreg cutting requires knowledge of acceleration rates and maximum head velocities. Figure 2.6 shows a typical velocity profile assuming linear acceleration and deceleration and that the length traversed is long enough to enable the head to reach its maximum velocity. A finite time is required to accelerate to the maximum velocity, decelerate at the end of the pass and turn after each pass. For very small parts, the automatic machine never achieves its full potential.

For this velocity profile, the time required to move a distance, d, is given by

$$t = d/v_{max} + v_{max}/a + \omega_t \qquad \text{for } d > v_{max}^2/a \tag{2.9}$$

where v_{max} is the maximum velocity, a is the acceleration rate and ω_t is the turn time. For cases in which the maximum velocity is not reached, the time required to transverse a distance, l, is given by

$$t = 2\ (l/a)^{.5} + \omega_t \qquad \text{for } l < v_{max}^2/a \tag{2.10}$$

The time required for any generalized pattern is the sum of the motion time and the turn around times.

During automatic prepreg tape layup, cutting of the tape and removal of the backing paper is done automatically. It is assumed that the layup head travels along the length of the part until it reaches the edge where it turns 360 degrees and continues to lay down tape in the opposite direction. The total tape layup cycle time, t_{TL}, is given by

$$t_{TL} = t_{tl} + t_{tc}\ N_r \tag{2.11}$$

where

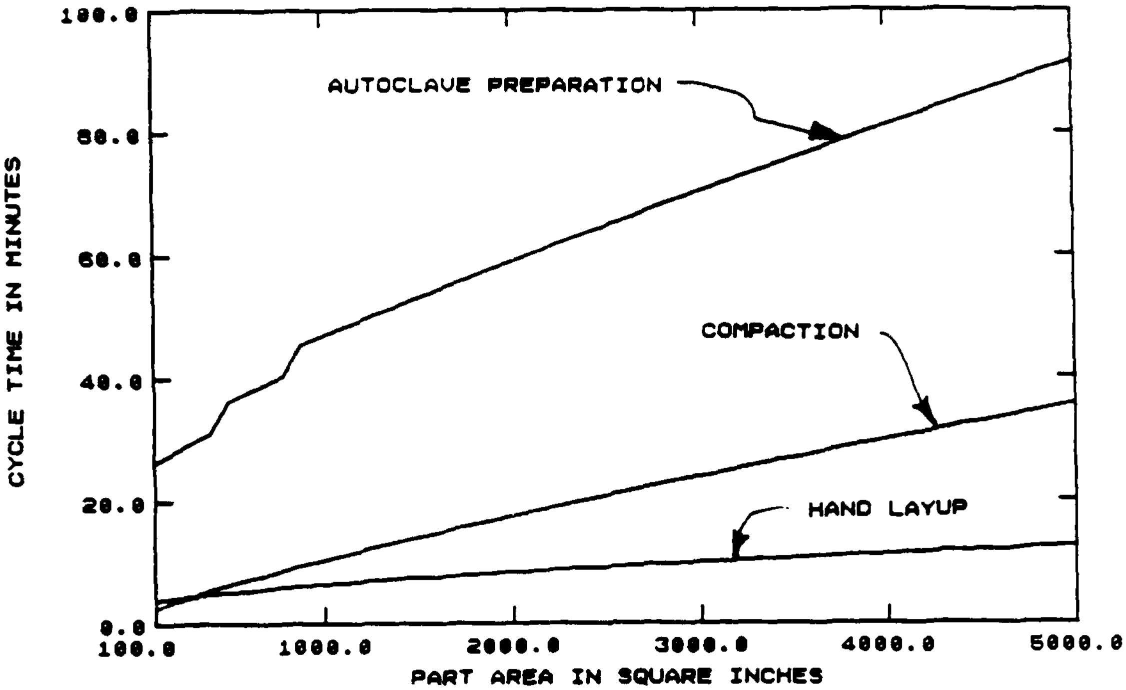


Figure 2.5 Cycle Times for Manual Tasks

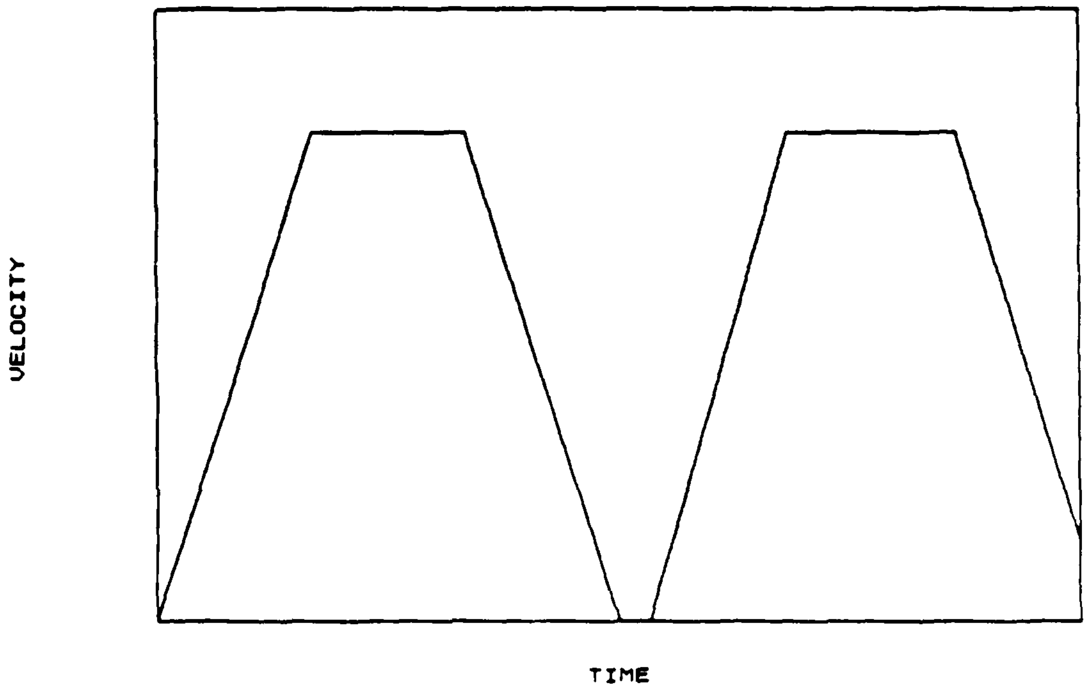


Figure 2.6 Typical Velocity Profile

$$N_r = N_p\, l_p\, w_p\, l_r/w_t$$

where t_{tl} is the tape layup time, t_{tc} is the tape reel changing time, N_r is the required number of reels, l_p is the length of the part, w_p is the width of the part, l_r is the length of tape per reel and w_t is the width of the tape. Prepreg generally is available in reels of 180 yards [34]. Eight minutes [35] are required to load the tape roll, thread the tape through the machine and empty the takeup reel and the tape width is typically 4 inches.

The tape layup time for a unidirectional rectangular part is given by

$$t_{tl} = N_p\,(w_p/w_t)\,(l_p/v_{tl} + v_{tl}/a_{tl} + \omega_{tl}) \qquad \text{if } l_p > v_{tl}^2/a_{tl} \tag{2.12}$$

$$t_{tl} = N_p\,(w_p/w_t)\,2\,((l_p/a_{tl})^{.5} + \omega_{tl}) \qquad \text{if } l_p < v_{tl}^2/a_{tl} \tag{2.13}$$

where v_{tl} is the maximum tape layup velocity, a_{tl} is tape layup acceleration and ω_{tl} is the turn around time. Typical values for v_{tl}, a_{tl} and ω_{tl} are 1000 in/min, 30,000 in/min^2 and .033 min, respectively [36]. Figure 2.7 shows layup time versus tape length for various acceleration rates. When the length of tape is short, the acceleration rate can have a significant effect on the layup time.

The complete cycle time for the automated cutting system, t_{AC}, is given by

$$t_{AC} = t_{ac} + t_p + t_k \tag{2.14}$$

where t_{ac} is the cutting time, t_p is the time required to plot out the part before cutting, t_k is the time to manually load and unload the cutting table and sort the pieces into kits. According to a time study by an aerospace company [37], the cutting system spends 20% of its operating time plotting the parts for verification, 6% of its operating time unloading and loading the fabric and 8% of its time is downtime.

Assuming no common edges, the automated cutting time is given by

$$t_{ac} = N_p\{2(l_p+w_p)/v_c + 4v_c/a_c + 4\omega_c\} \qquad \text{if } w_p > v_c^2/a_c \tag{2.15}$$

$$t_{ac} = N_p\{2l_p/v_c + 4(w_p/a_c)^{.5} + 2v_c/a_c + 4\omega_c\} \qquad \text{if } l_p > v_c^2/a_c \text{ and } w_p < v_c^2/a_c \tag{2.16}$$

$$t_{ac} = N_p\,\{4(l_p/a_c)^{.5} + 4(w_p/a_c)^{.5} + 4\omega_c)\} \qquad \text{if } l_p < v_c^2/a_c \tag{2.17}$$

where v_c is the cutting velocity, a_c is the acceleration and ω_c is the turnaround time. The cutting speed for a reciprocating knife ranges between 800 and 900 inches per minute [38, 39]. It is assumed that the acceleration time for the cutting systems is the same as that of the tape layup equipment.

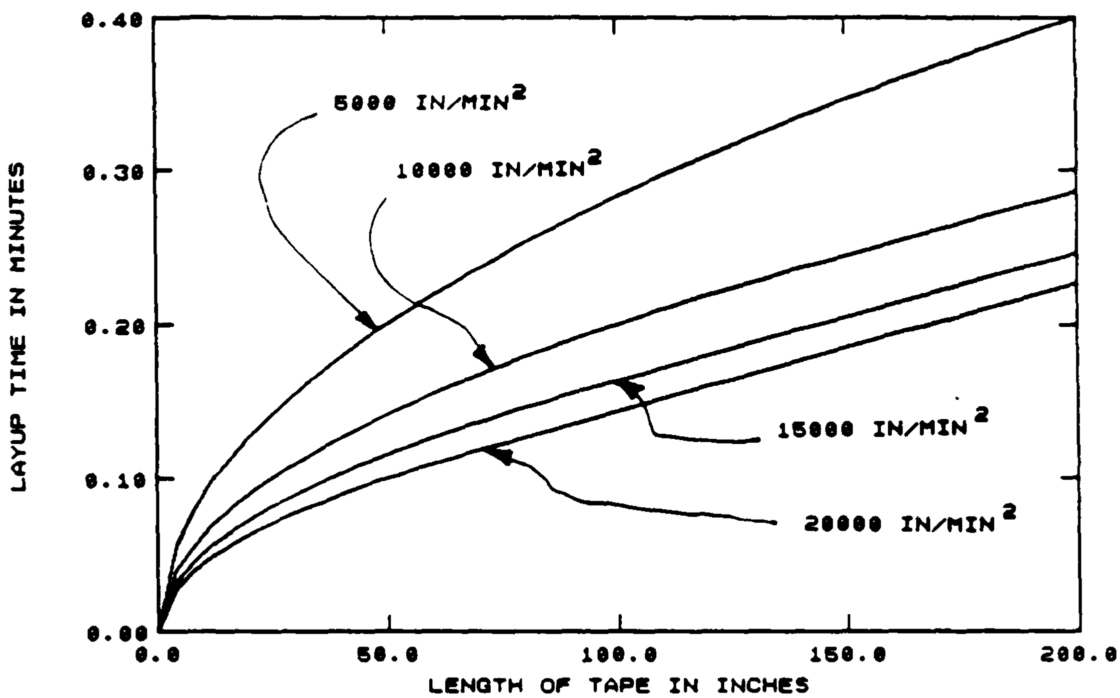


Figure 2.7 Tape Layup Cycle Times

Simpler models are used to determine the cycle times for robotic transfer, pultrusion and filament winding. The robot transfer cycle, t_{RT}, is approximately 37 seconds per ply and the transfer area is limited to 2000 square inches [40]. The pultrusion cycle time, t_{PL}, is estimated by

$$t_{PL} = l_p / v_p \tag{2.18}$$

where v_p is the pultruder rate which is about 8 in/min [41] for epoxy resin systems. The filament winding cycle time, t_{FW}, is given by

$$t_{FW} = V_p /(v_w A_c) + t_{MR} \tag{2.19}$$

where t_{MR} is the mandrel removal time of 15 minutes, V_p is the part volume, v_w is the winding velocity of 1200 in/min [42] and A_c is the cross sectional area of the resin impregnated fibers given by

$$A_c = \pi N_{ft} r_f^2/V_F \tag{2.20}$$

where N_{ft} is the number of filaments per tow, r_f is the filament radius and V_F is the fiber volume fraction. Typical values for the fibers per tow, fiber radius and fiber volume fraction are 12,000, .315 mils and .62, respectively [43].

For resin transfer molding, a simple model based on Darcy's law [44] for the flow through porous media can be used to determine the mold filling cycle time. For thin parts the resin flows in the plane of the fiber form with a velocity, q, given by

$$q = \frac{Q}{A_f} = - \frac{S}{\mu} \frac{dP}{dx} \tag{2.21}$$

where Q is the volumetric flow rate of the resin, A_f is the cross sectional area, μ is the resin viscosity, S is the permeability of the fiber form and dP/dx is the pressure gradient. Assuming a linear velocity profile and a linear pressure gradient integration gives

$$t_{MF} = \frac{\mu\, l_{rp}^2}{2\, S\, \Delta P} (1 - V_F) \tag{2.22}$$

where t_{MF} is the fill cycle time, l_{rp} is the maximum resin path length and ΔP is the change in pressure over this length. Since the resin has a finite geltime and permeability is related to fiber volume fraction, there is a tradeoff between maximum flow distance and fiber volume fraction. Table 5.6 gives values for geltime and viscosity for Shell EPON resin.

Besides this pressure criteria, the maximum output of the pumping equipment must also be considered. The minimum cycle time for maximum flow rate is given by

$$t_{MF} = \frac{(1 - V_F) V_p}{Q} \tag{2.23}$$

where V_p is the volume of the part. The actual cycle time is the maximum time computed from the pressure and flow rate criteria. Resin injection equipment is capable of pumping 18 lb/min and producing an input pressure of 25 lb/in^2 [45]. Typical permeabilities for three dimensional graphite braid are 20 to 1500 darcies [46].

In addition, it is necessary to calculate the time to demold the part, cut and layup the fiber form in the mold and prepare the mold. The demold and mold preparation time of 45 and 27 seconds are based on resin injection molding [47]. Since no other data was available, the cutting and layup time, t_{FL}, was estimated by using power law relationships developed by Northrop [48]. For the 200th part the cycle time in minutes for this part of the process is given by

$$t_{FL} = N_p \, .045 \, A_{ff}^{\; .6295} \tag{2.24}$$

where A_{ff} is the area of the fiber form. The press cycle time is simply the geltime.

Each of these cycle times must be corrected for process efficiency. For automated processes, the efficiency ratio is the equipment utilization ratio, which was assumed to be 90%. For manual operations, three correction factors for personal time, F_p, fatigue time, F_f, and delay time, F_d, are used to account for process efficiency. Fatigue time is dependent on the type of job, weight handled and the degree of repetition in a particular task. More physically demanding tasks such as hand layup and manual cutting will have a higher fatigue correction factor than less demanding tasks such as the operation of automated equipment. Delay time is due to equipment downtime, lack of work, and foreman instructions. The cycle time is increased by the sum of these factors which are summarized in Table 2.3.

Table 2.3 Correction Factors for Manual Operations [49]

	F_f	F_p	F_d
Manual Labor	25%	5%	5%
Operator	15%	5%	5%
Skilled Labor	15%	5%	5%

2.3.2.2 Learning Curve

The cycle times are also adjusted to account for learning. The learning or improvement curve is a geometric progression that expresses the decreasing input required to accomplish any repetitive operation. Empirical evidence suggests that the time or cost necessary to complete a unit of production will decrease by a constant percentage each time the production quantity is doubled. This progress is not just explicit learning or improvement in the performance of one individual at a specific task but also the progress of an organization which learns to do a job better. The first article on learning curves based on the analysis of empirical data was published by Wright [50] in 1936. Although there have been many developments in learning curve theory since then, because the estimation of the parameters for more complex models has been a difficult task, the average unit curve by Wright remains the most popular.

The linear cumulative average curve theory by Wright suggests the following relationship between labor time and units produced

$$y^i_{ave} = y_1 \, i^b \tag{2.25}$$

where y^i_{ave} is the average production time for any quantity i, i is the number of units completed, y_1 is the number of labor hours for the first unit and b is the slope of the learning curve plotted on log-log scale. A curve is frequently designated by its percentage slope. A curve with a value of b = -.322 is an 80% curve. This means that the average time to produce a quantity of parts is 80% of the average time to produce one half that number of units.

Since the learning curve characteristic is dependent on the volume of production, complexity of product, methods of engineering organization and the type of manufacture, each manufacturer must develop his own characteristic for typical operations. Wright found that the learning characteristic for the airframe industry was 80%. An article by Conway and Schultz [51] quotes values between 67.8 and 95.8%. Nadler and Smith [52] reported values of 77.5 to 87.4% for machine tool shops and 69 to 98.5% for a variety of other industries. Figure 2.8 shows the learning curve for several learning characteristics. After 200 completed units, there is little change in the average cycle time.

For new manufacturing methods, it is necessary to predict a learning coefficient. McCampbell and McQueen [53] suggest that the learning curve coefficient is a function of the percentage of manual labor. A completely automated process in which there is no capacity to improve would have a 100% learning curve whereas a labor intensive manual process would have a 60% learning curve. The learning curve characteristic, C, for a process with several tasks would be given by

$$C = \sum_{i=1}^{n} m_i c_i \tag{2.26}$$

where m_i is the percentage of cycle time and c_i is the learning characteristic for that operation.

Since it is difficult to estimate the cycle time or production cost for the first unit, the average cycle time for 200 units is frequently used instead. The unit time for the ith unit is given by

$$y_i = y_1(i^{b+1} - (i-1)^{b+1}) \tag{2.27}$$

The production time for the first unit in terms of the 200th unit is given by

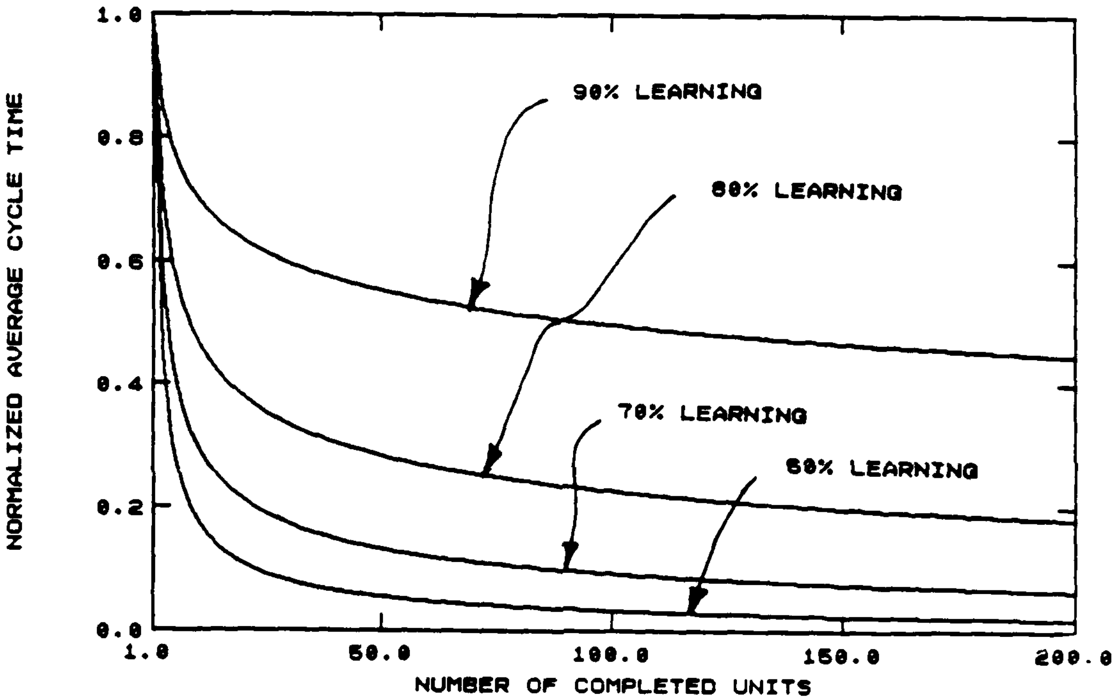


Figure 2.8 Normalized Cycle Times for Several Learning Curves

$$y_1 = y_{200}/(200^{b+1} - 199^{b+1}) \tag{2.28}$$

One shortcoming of the learning curve is that the rate of production increases indefinitely as the firm produces more and more of the product. To overcome this lack of realism, it is generally assumed that the production eventually levels off. In this study, it is assumed that the learning curve levels off at 1220 units, the production volume at which the average production time is equal to the production time of the 200th unit.

Another important consideration in the theory of learning curves is the effect of production breaks. After producing a batch j with Q_j units, frequently there is a gap in production of sufficient length so that some of the learning accumulated in producing these units is not retained when production starts up again. According to Anderlohr [54], the loss of learning can be expressed in equivalent units, α_j:

$$\alpha_j = Q_1 + \sum_{i=2}^{j} (k\, Q_{i-1} + Q_i) \tag{2.29}$$

The average production time for α_j batches is given by

$$y_{ave} = y_1\, \alpha_j^{\,b} \tag{2.30}$$

Anderlohr describes a simple method to determine the learning loss. He claims that the learning loss is due to five factors: (1) production personnel learning, (2) supervisory learning, (3) continuity of production, (4) improvement of special tooling and (5) improvement of methods. The percent loss of each of these factors are determined and then evenly weighted and summed to determine the total learning loss factor. Typical loss factors are 50% loss over a three to six month period and 75% percent loss over a twelve month period. Figure 2.9 shows the equivalent batch size for different loss factors.

2.3.2.3 Labor Rates

Labor rates are dependent on the skills of the laborer and the type of task. Skilled laborers, such as equipment programmers, generally command a higher wage than other workers. An hourly wage of $15/hour for manual laborers and operators was based on information compiled by the Department of Labor on earnings of aircraft part manufacturers in the United States in 1984 [55] and inflated to be representative of 1988 values. The skilled wage was $20/hour. Fringe benefits increased the wages by 30% [56]. There are 250 working days per year and 8 hours per shift.

2.3.3 Material Costs

Material costs can vary substantially depending on the process. The prepreg material costs are given by

$$C_M = \rho_p\, V_p\, c_p\, (1 + F_s)(P/A, i, T) \tag{2.31}$$

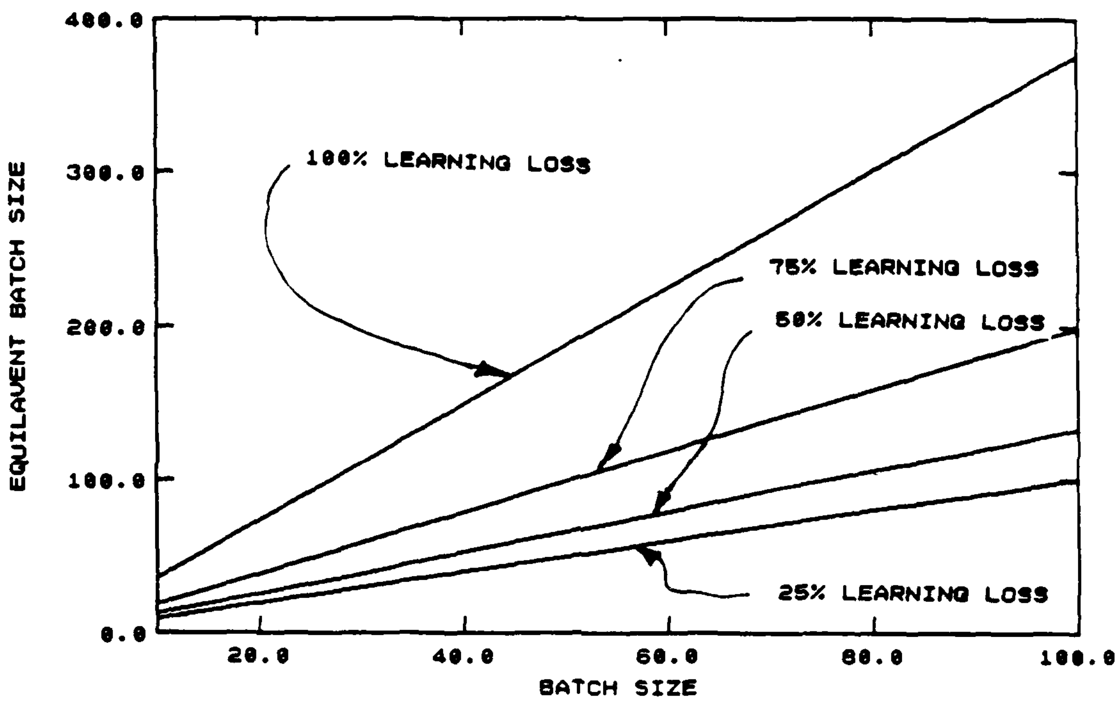


Figure 2.9 Equivalent Batch Sizes for Learning Loss Parameters

where

$$V_p = N_p \, l_p \, w_p \, t_p$$

where ρ_p is the density of prepreg, c_p is the price of the prepreg material per unit weight and F_s is the scrap factor which includes all non recyclable material which is lost during processing. For wet processes, the cost of materials is given by

$$C_M = V_p \left(V_F \rho_f c_f + (1 - V_F) \rho_r c_r\right)(1 + F_s)(P/A, i, T) \qquad (2.32)$$

where ρ_f is the fiber density, c_f is the fiber cost, ρ_r is the resin density and c_r is the resin cost. Typical resin and fiber densities are .0455 and .065 lbs per cubic inch, respectively.

Continuous 12K graphite fiber typically costs twenty one dollars per pound [57] and neat epoxy resin costs ten dollars per pound [58]. For RTM, the type of reinforcing material used will be dependent on the part design. Three dimensional forms are the most expensive at $75/lb [59]. Two dimensional forms range from $30/lb for carbon biaxial mat [60] to $55/lb for 3K woven graphite mat [61]. For the examples in Section 3, the fiber volume fractions are .47 for RTM and .65 for all other methods. There is a considerable material cost difference as shown in Table 2.4.

Table 2.4 Material Costs Parameters

	Price / lb	F_S
Manual Production	$46.0	20% [62]
Automated Ply Cutting	$46.0	12%
Robotic Transfer	$46.0	12%
Tape Layup	$46.0	10%
Filament Winding	$18.0	7%
Pultrusion	$18.0	7% [63] 10% [64]
Resin Transfer Molding	$46.5	7%

2.3.4 Tooling Costs

Tooling costs are a function of the part area, the tool lifespan and the production requirements. The number of tools used is dependent on the tool lifespan as well as the number of different parts produced since each unique part requires a new tool. For epoxy graphite tooling, the cost is given by

$$C_T = N_t \left(t_T L_s + c_{ts} \, l_p \, w_p + c_{sb} A_{sb}\right) (P/A, i, T)/N \qquad (2.33)$$

where N_t is the number of tools, t_T is the time to fabricate the tool, c_{ts} is the tool surface material costs, c_{sb} is the tool support board cost and A_{sb} is the area of the tool support boards. The tool surface materials cost $.67/in^2 and the support board costs \$.60/in^2 [65]. The fabrication time is approximately ten man hours per square foot [66]. Graphite epoxy tools last 500 cycles [67].

A power law relationship, based on information from an equipment manufacturer [68], is used to determine the cost of filament winding mandrels. The mandrel cost is given by

$$C_T = N_m\, 144.5\, (l_p\, w_p)^{.477}\, (P/A, i, T)/N \tag{2.34}$$

where N_m is the number of mandrels and in this equation the part dimensions are in feet. The pultrusion die cost per part is given by

$$C_T = N_d\, c_d\, (P/A, i, T)/N \tag{2.35}$$

where N_d is the number of dies and c_d is the cost of a single die. A simple two piece rectangular die costs about five thousand dollars [69]. The life span of a die and mandrel is approximately 200,000 cycles [70]. The cost of RTM tooling is approximately seven times the cost of autoclave cure tooling and typical lifespans range from 3,000 to 4,000 cycles [71, 72].

2.4 Indirect Costs

There are several indirect costs which will be affected by the adoption of these alternative manufacturing technologies. Klahorst [73] in an article on justifying flexible manufacturing systems has identified several critical indirect costs including work-in-progress inventory, floor space, indirect labor for quality control, supervision, shop scheduling and engineering, and rework and scrap which are relevant to this economic comparison.

2.4.1 Inventory Costs

Three kinds of inventory must be considered: raw materials, work-in-progress and finished goods. The raw materials and finished goods inventory levels are dependent on the ordering and shipping policies of the firm. Small batch systems tend to reduce finished goods inventory levels but increase the need for raw materials. The work-in-progress inventory is dependent on batch size and scheduling policies.

The work-in-progress inventory cost, I_{wip}, is based on the average annual inventory and can be expressed as

$$I_{wip} = \sum_{i=1}^{N} (V_i\, c_i\, t_i\, c_c)/2 \tag{2.36}$$

where V_i is the production volume of part i, c_i is the value added to part i, t_i is the throughput time of part i, c_c is the inventory carrying cost and N is the total number of parts. The inventory carrying cost is expressed as a percentage and includes cost of money, storage, handling, damage, loss, obsolescence and taxes.

These costs range from 12 to 30% of the value of inventory per year [74]. The throughput time is given by

$$t_i = t_s/b + t_h + t_c + t_w \tag{2.37}$$

where t_s is the setup time, b is the batch size, t_h is the part handling time, t_c is the cycle time and t_w is the waiting time.

2.4.2 Facilities

The plant facilities costs are proportional to the floor space required. The current market value ranges between $20-35 per square foot [75]. The floor space for hand layup corresponds to the tool area plus an additional six foot aisle around the perimeter of the equipment to facilitate materials handling. Table 2.5 gives floor space requirements for automated equipment.

Table 2.5 Automated Equipment Floor Space

automated cutting	1326 ft^2
transfer robot	324 ft^2
automated tape layup	651 ft^2
pultrusion	450 ft^2
filament winding	388 ft^2
RTM pump	144 ft^2
RTM press	256 ft^2
Autoclave and Oven	736 ft^2

2.4.3 Indirect Labor

Indirect labor costs are generally pooled and distributed to a part on the basis of direct labor hours. Table 2.6 gives the indirect labor multipliers used by Northrop [76] for manual production. Quality control includes the time to inspect parts manually during and after fabrication. Tooling labor involves the repair and maintenance of layup tools. The effort necessary to improve the manufacturing plan, assist in manufacturing process and process company generated changes encompasses the manufacturing labor. Engineering involves the liaison and analysis in support of manufacturing. Graphics supports engineering and manufacturing with activities such as process and control of engineering drawings.

Table 2.6 Indirect Labor Multipliers

Quality control	.124
Tooling	.111
Manufacturing	.197
Engineering	.073
Graphics	.016

The effect of automated technologies on the required indirect labor is difficult to quantify. Klahorst has given some guidelines for comparison. Automated systems generally eliminate many inspection needs. Since the amount of on-line inspection required is in direct proportion to the number of direct labor workers, systems which reduce direct labor reduce the chance of human error. Supervision varies in direct proportion to the number of workers and machines involved. One supervisor is needed for every 17 NC machines, every 50 transfer stations, 18 conventional machines and 18 direct labor workers. Introduction of NC and CAM equipment can reduce hourly factors for average engineering changes by 33% and 30%, respectively.

2.4.4 Rework and Scrap

According to Klahorst, the more highly automated systems can reduce scrap levels 40 to 60%, but it is difficult to generalize these numbers. In many industries, costs for correcting poor quality can exceed 30% of the total process cost. Eighty percent of quality defects are in the design phase or by purchasing policies that value low quality over price of parts and materials [77]. Twenty percent of quality defects are attributed to processing.

3. ECONOMIC ISSUES

3.1 Introduction

The economic model was used to compare the cost of fabricating flat laminates by several alternative manufacturing processes. The objective was to determine the production volumes at which alternative methods were able to compete with manual production and identify factors which contribute to this cost savings. In this section, it is assumed that each method produces parts of identical quality. The manufacturing costs for high demand production are compared. The sensitivity of these results to part geometry and material, labor and equipment parameters are then presented. Following a comparison of indirect costs, the results of the cost analysis are summarized in the final subsection.

3.2 Direct Costs for High Demand Production

Figure 3.1 shows the fabrication costs for a 12 inch by 48 inch, 24 ply, 4.1 pound part by each process as a function of annual production volume. In general, the manufacturing cost is higher at low production volumes since the equipment depreciation is spread over a smaller number of parts. For these low production volumes, typical of the aerospace industry today, the automated prepreg processes are not competitive with manual layup of prepreg since the reduction in direct labor does not offset the capital investment in equipment. The wet processes are, however, able to successfully compete due to low equipment and material costs.

Pultrusion, which is a continuous one step process, appears to be the most cost effective process. Pultrusion benefits from relatively low equipment and material costs and a high production rate. It is, however, severely limited in part geometry and fiber orientation. Resin transfer molding and filament winding with oven cure offer similar cost savings but a wider variety of possible part shapes and fiber orientations. Although use of the autoclave to cure filament wound parts substantially increases the cost of filament winding, this method offers cost savings over manual production and automated prepreg methods for annual production volumes over 500 parts.

A breakdown of the costs for each manufacturing method for an annual production rate of 5,000 parts is shown in Figure 3.2. In manual production, material costs account for over half the direct cost and almost three times the cost of direct labor. With the exception of RTM, which utilizes expensive preform fibers, the wet processes offer substantial reduction in material costs. This effect, however, may be reduced as indicated by a recent study [78] which concludes that the prepregging operation could be moved in-house at a substantial savings. In addition, equipment costs for pultrusion and RTM are substantially lower. At this production volume the automated prepreg methods give a slight decrease in material costs due to reduction in raw material scrap but require a greater investment in equipment. Note that automated cutting results in an increase in direct labor costs. Even though the automated cycle time is

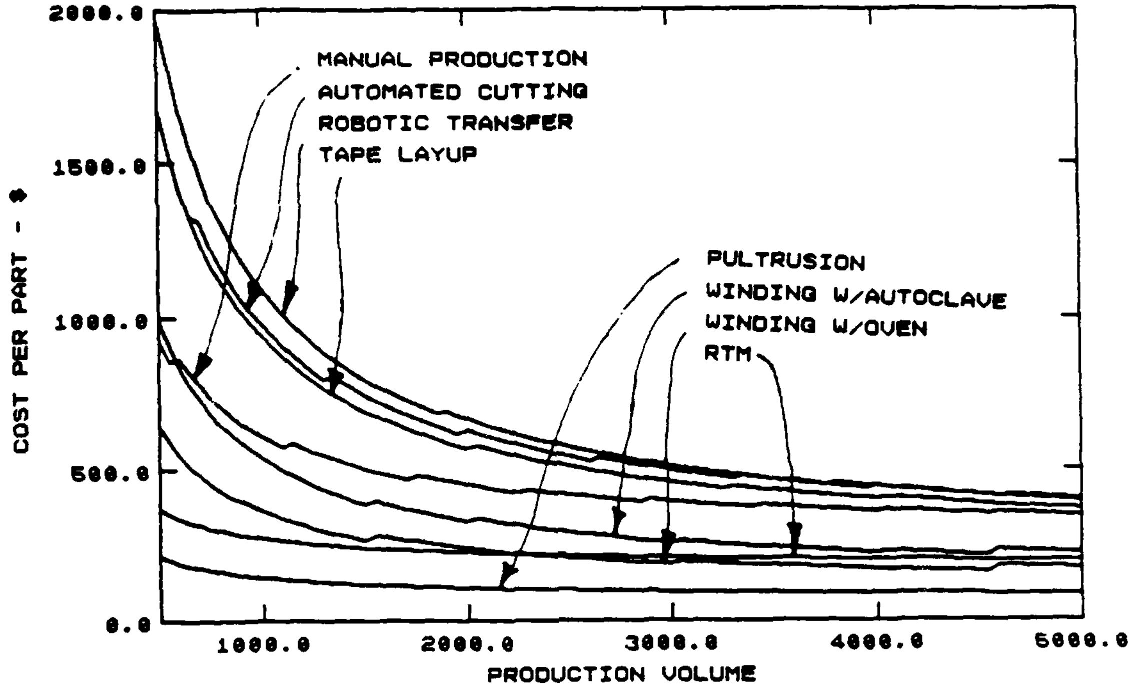


Figure 3.1 Fabrication Costs for a 24 Ply 4.1 lb Laminate

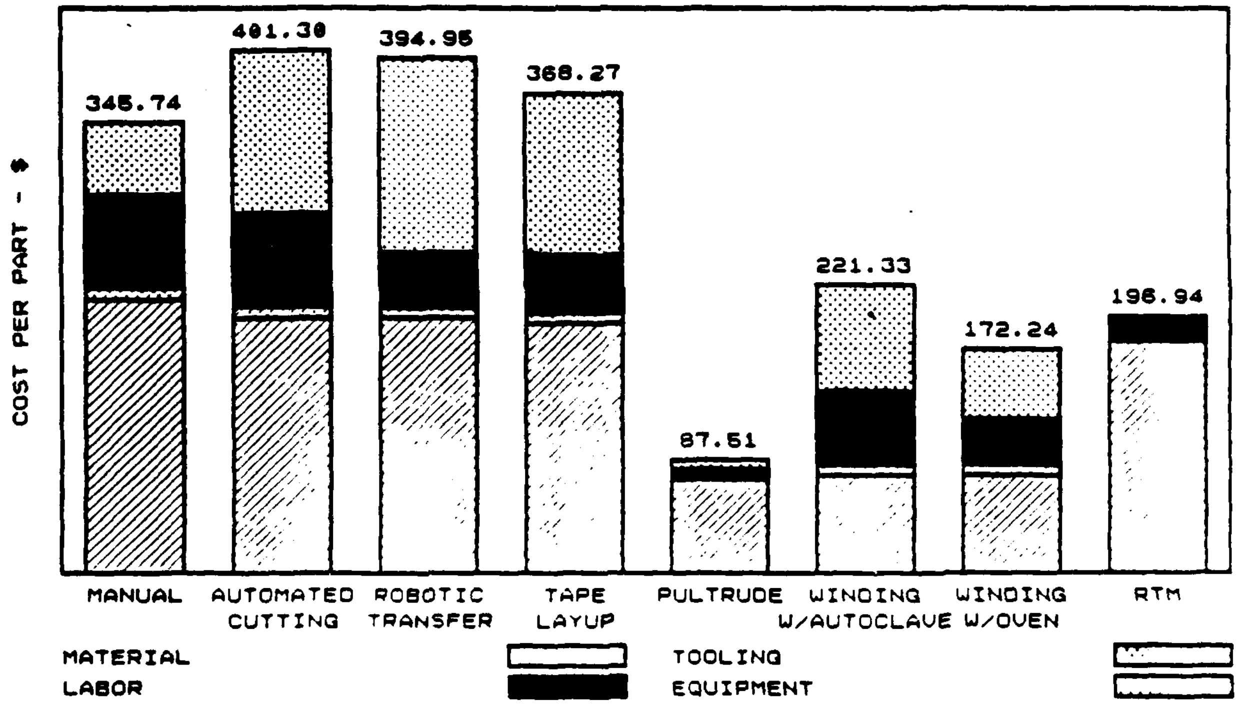


Figure 3.2 Cost Breakdown for an Annual Production Volume of 5,000 Laminates

lower, an operator is required during idle time. Robotic transfer offsets this effect by a more substantial decrease in cycle time for layup operation.

Figure 3.3 shows the breakdown of cycle times without the autoclave cure cycle for each process for batch production of over 1,200 parts. All the automated methods offer a decrease in cycle time with RTM and pultrusion offering the most substantial reduction. Note that, with the exception of RTM and pultrusion, each of these processes requires an additional six hour cure cycle. Compaction during the manual layup process accounts for over 30% of the manual labor cycle time. The reduction in cycle time by the automated prepreg methods is primarily achieved by eliminating the compaction process. Only a 25% and 50% decrease in layup time is realized by tape layup and robotic transfer. The winding time is longer than that required to manually cut and layup the prepreg. If compaction were necessary, the cycle time for filament winding would be higher than that of manual methods. The model predicts a 54% savings in cycle time for tape layup over manual production. This is very close to the 58% cost savings reported in a recent article [79].

Higher annual production rates favor the use of automated prepreg methods over manual production as shown in Figure 3.4. Discontinuities in the cost are caused by the introduction of parallel equipment lines, additional tools or an additional shift of laborers to meet specified annual production volumes. For example, as the figure indicates, the need for a parallel tape layup machine at approximately 10,000 and 20,000 parts per year represents a substantial increase in part cost. As production volumes increase, the cost of automated prepreg processes eventually fall below that of manual production. Figure 3.5 illustrates that as production volumes are increased, the cost of filament winding with autoclave cure falls below the cost of RTM and approaches the cost of filament winding with oven cure. RTM is better suited for firms with moderate production volumes.

The manufacturing cost reaches a steady state value at high production volumes. Figure 3.6 shows the cost breakdown for an annual production rate of 25,000 parts. Comparison of this bargraph to Figure 3.2 indicates that at this higher production volume material represents a higher percentage of the cost than equipment. As indicated by Table 3.1, the equipment utilization is more efficient at this steady state manufacturing cost. The 1.5% to 7.6% cost savings offered by the machine assisted prepreg methods is mainly attributed to a reduction in scrap and waste due to nesting and more efficient use of materials. The capital investment in equipment is offset by a labor reduction for robotic transfer only. Automated cutting and tape layup have higher combined labor and equipment costs than manual production. These methods would not be cost effective at this production volume if manual production had the same scrap rate.

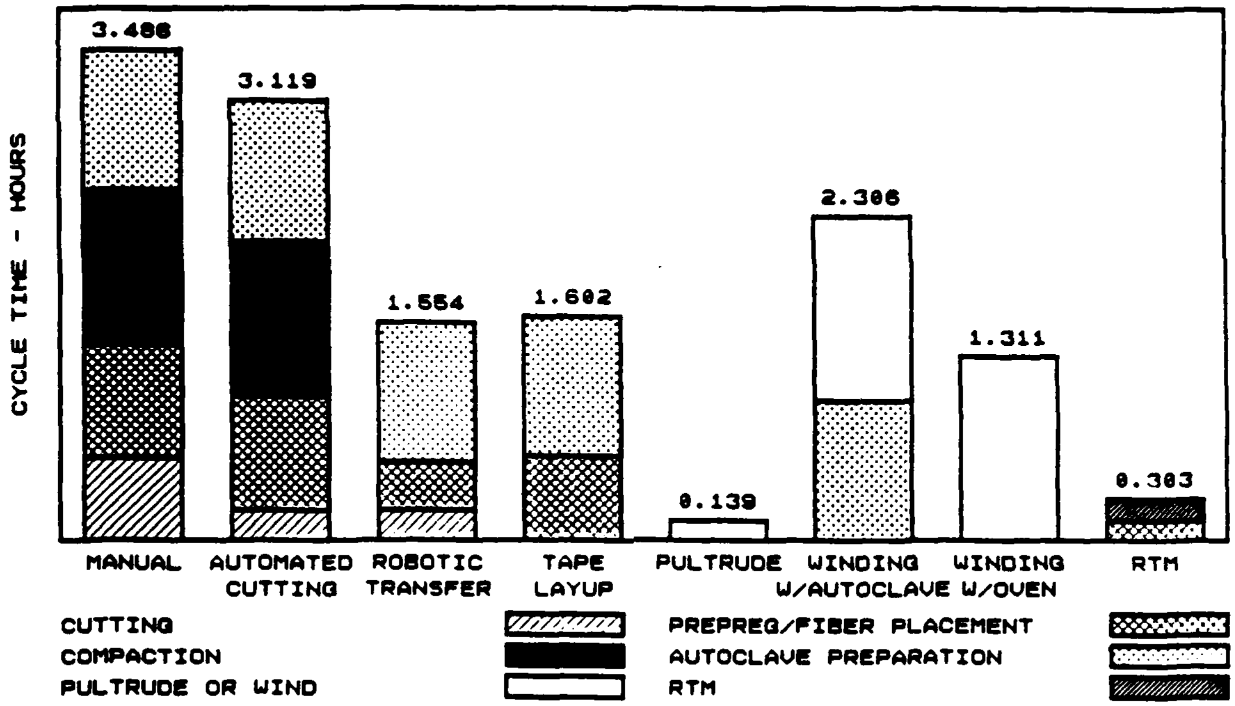


Figure 3.3 Cycle Times for a 24 Ply 4.1 lb Laminate

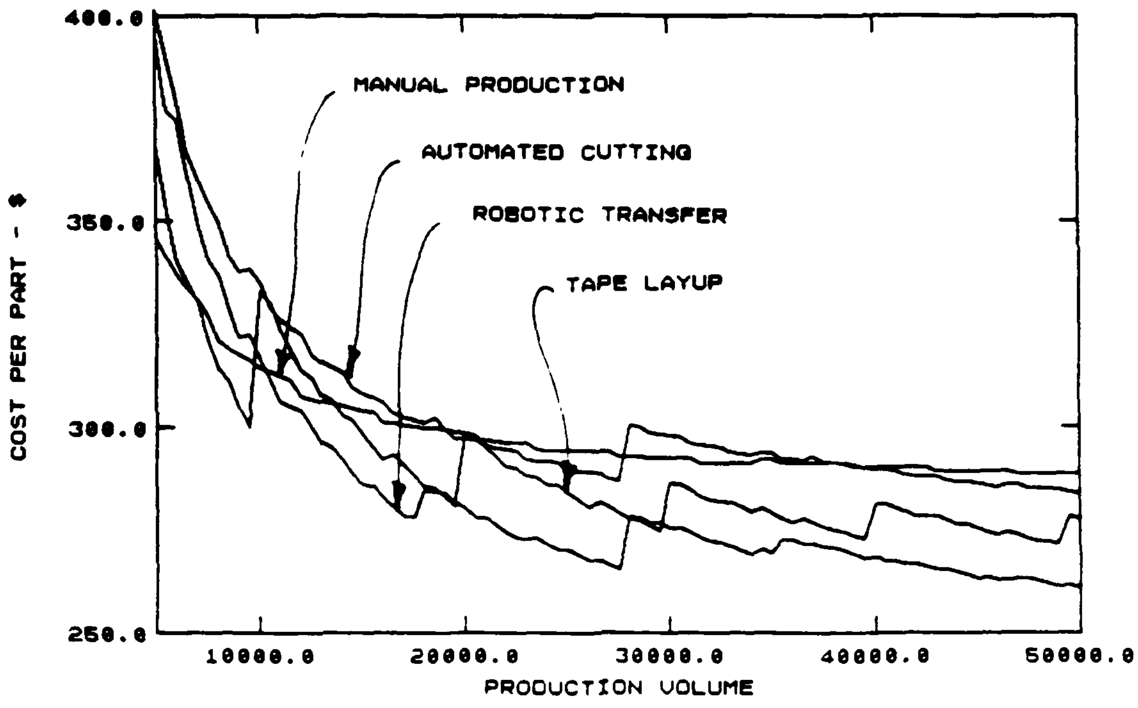


Figure 3.4 Fabrication Costs for Prepreg Methods

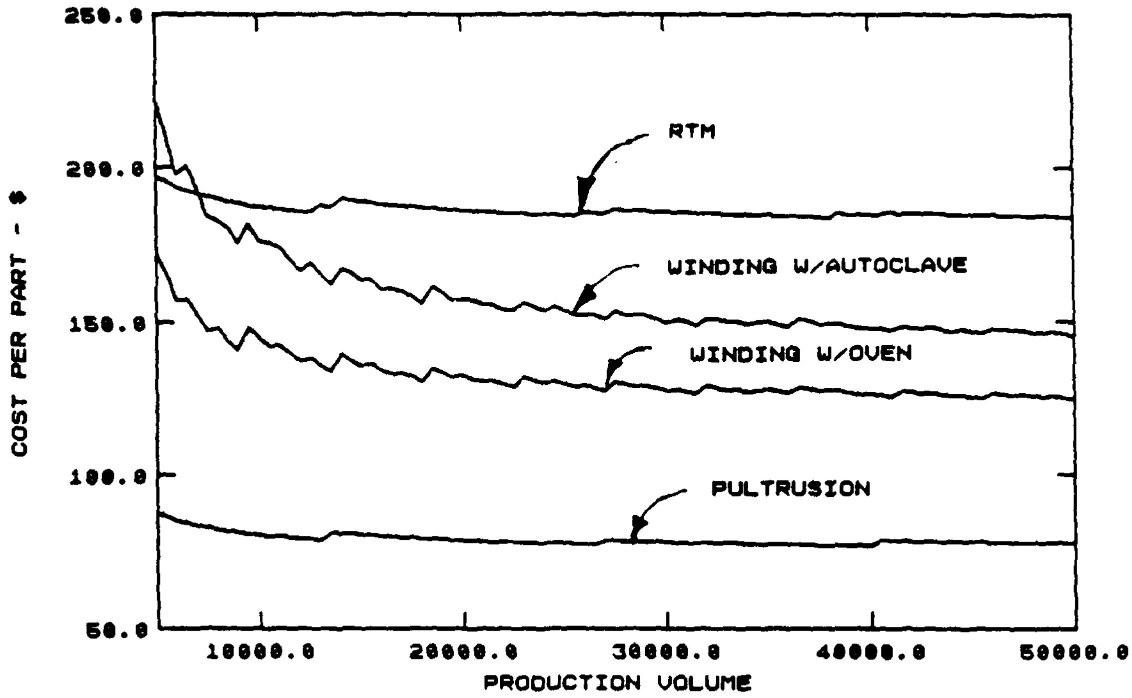


Figure 3.5 Fabrication Costs for Raw Material Methods

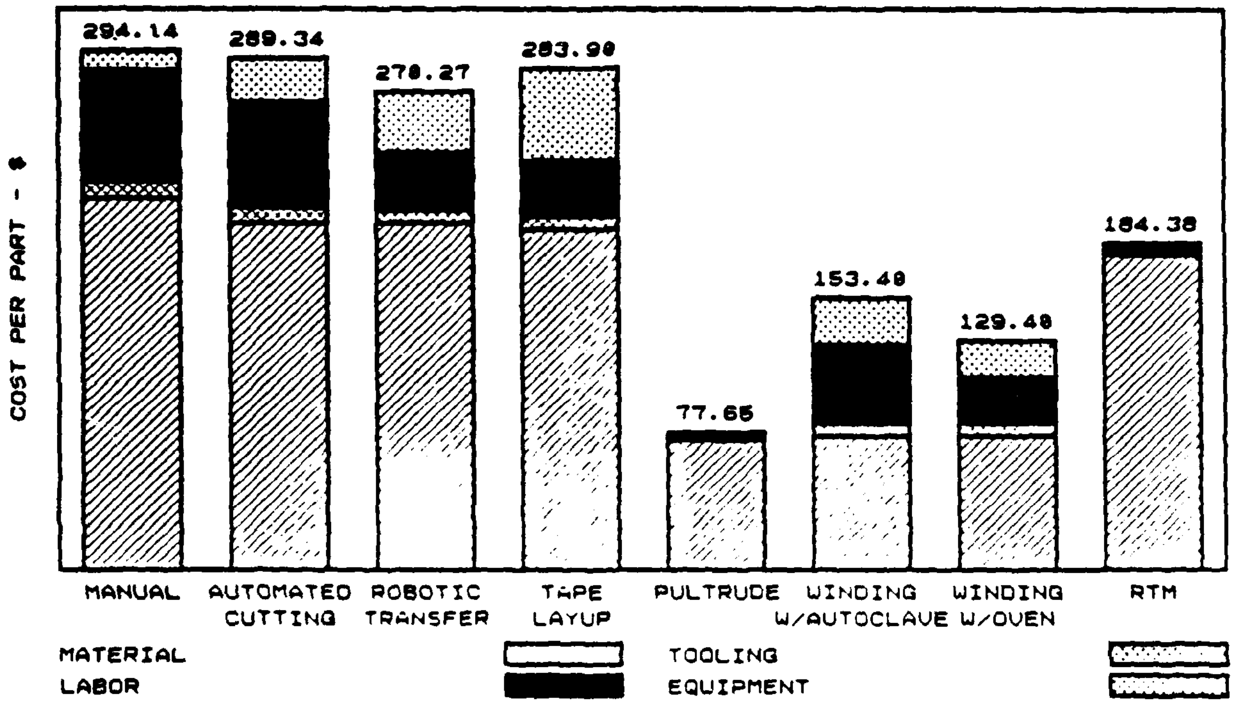


Figure 3.6 Cost Breakdown for an Annual Production Volume of 25,000 Laminates

Table 3.1 Maximum Equipment Capacity per Shift

	parts
automated cutting	9,238
transfer robot	5,837
tape layup	3,293
pultrusion	13,396
filament winding	1,519
RTM	12,800

The wet processes decrease manual production costs by 73.6%, 47.8%, 56.0% and 34.8% for pultrusion, filament winding, filament winding with oven cure and resin transfer molding, respectively. At this high volume, pultrusion is a highly economical process with its minimal equipment, tooling and labor costs contributing only 5.6% to the total manufacturing cost. Filament winding reduces the equipment and labor costs by only 6% but decreases the material costs by over 60%. The replacement of autoclave with an oven results in a 15.6% decrease in cost. Similar to the cost breakdown for pultrusion, the equipment, tooling and labor costs for RTM represent a small percentage of the total cost. Material costs, however, can be substantial due to the high cost of fiber forms. For this example, the RTM material costs are only slightly below those for manual production.

The automated prepreg methods do not breakeven with manual production until very high volumes. Although tape layup breaks even at 30,600 lbs, after producing 41,000 lbs it is no longer cost effective due to the need for parallel tape layup machine. Automated cutting and robotic transfer break even at 72,900 and 42,400 lbs, respectively. These volumes are extremely high in comparison to usage of composites today. According to a recent article [80], the total annual usage of graphite/epoxy prepreg for commercial aircraft in 1985 was only 420,000 pounds and only eight companies in the United States used over 60,000 pounds of prepreg annually. A new market study [81] estimates the annual production as 3.0, 1.0, .4 and 6.0 million lbs of prepreg for hand layup, machine assisted layup, pultrusion and filament winding, respectively.

3.3 Sensitivity Analysis

The previous results were based on many assumptions about part dimensions and equipment, material and labor parameters. It is important to evaluate the sensitivity of these results to changes in these parameters. In this section, the effect of parameter changes on the breakeven points and the steady state cost at higher production volumes will be discussed. Note that breakeven points can be very sensitive to the chosen parameters, since frequently these points are determined by the intersection of two lines with only slightly different slopes.

3.3.1 Sensitivity to Part Geometry

Figure 3.7 shows the variation in normalized cycle time versus part area for a rectangular part. Although generally the cycle time excluding the autoclave cure cycle increases with increases in part area, this cycle time

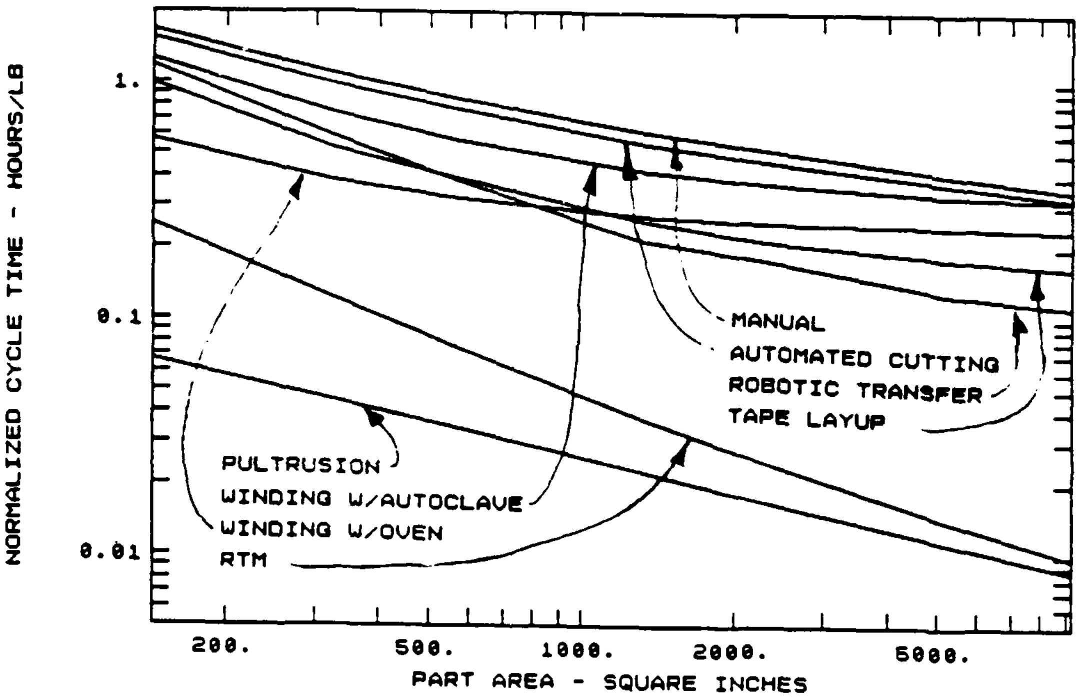


Figure 3.7 Cycle Time as a Function of Part Area

normalized by the weight decreases with part area for the all methods except filament winding with oven cure. The normalized cycle times for methods which require autoclave cure decrease due to the power law relationship between hand layup, compaction and autoclave preparation times. As part area for these tasks increases, the incremental gain in cycle time decreases substantially as shown in Figure 2.5. Pultrusion and resin transfer molding exhibit a greater decrease in normalized cycle time since their rates are proportional to only one dimension. Since the filament winding rate is directly proportional to the part volume, the winding cycle time per pound is constant despite changes in area.

The relative difference in cycle time between handlayup and the alternative processes will determine whether the breakeven points and the steady state cost will change. As part size increases the normalized cycle times for manual production, automated cutting and tape layup decrease at similar rates. Robotic transfer exhibits a larger decrease in cycle time than manual production whereas the normalized cycle time for filament winding approaches the cycle time for manual production. RTM and pultrusion exhibit the greatest decrease in normalized cycle time relative to manual production. Table 3.2 compares the breakeven points for a 4 ft^2 and 64 ft^2 part. Regardless of part area, pultrusion, RTM and filament winding with oven cure breakeven for all production volumes. For areas less than 2 ft^2, machine assisted prepreg methods do not breakeven. As the part areas increase, however, the breakeven points increase for these processes. This is expected for filament winding since the relative cycle time and therefore the labor cost increases. Although automated prepreg methods experience a reduction in normalized cycle time, the decrease in cost due to manual labor savings is greater than that caused by a decrease in automated cycle time.

Figure 3.8 shows the normalized cost versus part area for an annual production volume of approximately 100,000 pounds. As part area increases from one to 64 ft^2, the manual production cost per pound declines by 36%. The automated prepreg methods experience a similar decrease in normalized cost as the part area increases. Production of larger parts is slightly more beneficial to robotic transfer since the decrease in cycle time is greater. For filament winding with autoclave cure, the normalized cost decreases with increasing part area and approaches the cost per pound of oven cured parts. The normalized cost of RTM and pultrusion decrease slightly with part area.

Table 3.2 Breakeven Points Versus Part Area in 1,000 lb

process	4 ft^2	64 ft^2	increase
automated cutting	72.9	91.6	26%
robotic transfer	42.4	63.2	49%
tape layup	30.6	45.5	49%
filament winding	2.4	3.34	39%

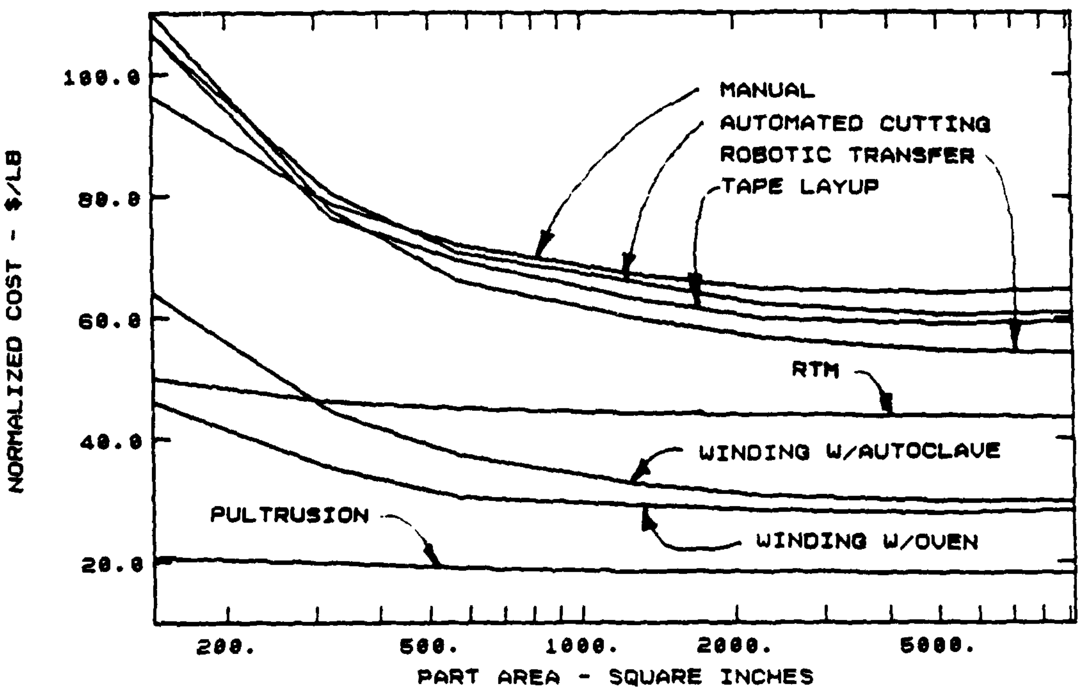


Figure 3.8 Fabrication Costs as a Function of Part Area

The normalized cycle time decreases for all methods except filament winding with oven cure as the number of plies increases. For methods which require autoclave cure, this effect is caused by the decrease in autoclave preparation time per unit weight as the number of plies increases. For pultrusion and RTM, the normalized cycle time decreases dramatically because the cycle time is not a function of part height. For the methods which use the autoclave, there was an $8/lb reduction in cost as number of plies increases from 18 to 512. Despite the high reduction in cycle time for pultrusion and RTM, the cost is insensitive to number of plies since equipment and labor are not major contributors to the manufacturing cost.

3.3.2 Sensitivity to Material Parameters

The prepregging process increases material cost by over 250%. Table 3.3 shows the breakeven points for prepreg market values ranging from the current cost of raw materials of $18/lb to the current prepreg cost of $46/lb. Both manual and machine assisted layup methods benefit from the reduction in prepreg cost. Since the scrap rate for manual production is higher than that for the automated prepreg methods, the breakeven points for machine assisted layup of prepreg increase slightly as the prepreg cost declines. Automated cutting, which as noted previously competes by reducing scrap, does not breakeven with hand layup for the lowest prepreg cost. The reduction of prepreg cost has the most dramatic effect on the relative savings achieved by the raw material methods. Figure 3.9 shows the savings at an annual production rate of 25,000 parts. Note that even without a materials cost difference, raw material methods compete successfully with manual production.

Table 3.3 Breakeven Points Versus Prepreg Cost in 1,000 lb

process	$18/lb	$28.75/lb	$46/lb
automated cutting	-	108.2	73.0
robotic transfer	54.1	51.2	42.2
tape layup	37.7	33.0	30.6
filament winding	11.8	4.8	2.4

The sensitivity of the cost to increases in prepreg and raw material costs will depend on the contribution of materials to the total cost. As the annual production rate increases, materials represent a higher percentage of the cost due to the decrease in equipment costs per unit. The economics of pultrusion and RTM is very sensitive to the materials costs. A dramatic change in equipment and labor costs will not be as significant as a small reduction in materials. For the automated prepreg methods, manual production and filament winding with oven cure, materials account for 50% to 70% of the total cost. For filament winding with autoclave cure, materials represents a much lower percentage of the cost.

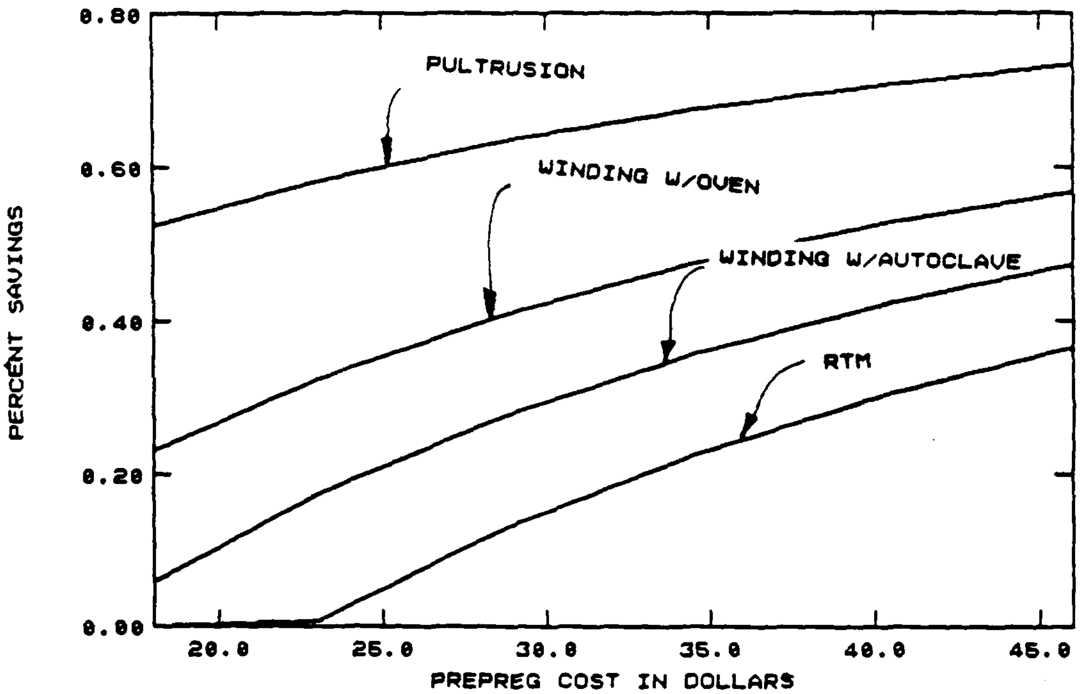


Figure 3.9 Relative Cost Savings as a Function of Prepreg Cost

Since the machine assisted layup processes compete by reducing scrap, it is important to evaluate the sensitivity of breakpoints to the manual scrap rate. Table 3.4 shows breakpoints assuming no scrap for the automated prepreg methods and varying scrap rates for manual production. As the relative scrap rates increase, there is a large difference in the production volumes necessary to economically compete with manual production. Automated cutting will not breakeven for production volumes less than 25,000 parts if the scrap rate is less than 10%. The breakeven points decrease rapidly for increasing scrap rates. The breakeven point for tape layup is less sensitive than that of automated cutting and robotic transfer.

Table 3.4 Breakeven Points Versus Manual Scrap Rate in 1,000 lb

process	0%	10%	20%
automated cutting	-	61.2	36.6
robotic transfer	64.9	37.6	30.6
tape layup	36.6	29.4	21.2

3.3.3 Sensitivity to Labor Parameters

Comparison of Figures 3.2 and 3.6 indicate that the labor component of the overall manufacturing cost is less sensitive to the production volume than the contribution of equipment. Filament winding is the most sensitive to labor rates due to high cycle time relative to material and equipment costs. For manual production, automated cutting and filament winding with oven cure, labor accounts for approximately 20% of the cost. The remaining processes are relatively insensitive to changes in the labor costs, which are less than 12% of the total cost. The breakeven points are sensitive to the labor rate, since it is the high labor component of manual production at low production rates which results in lower breakeven points. Table 3.5 shows the breakeven points for a few labor rates. Note that breakeven points for filament winding are insensitive to labor rates, since equipment and material cost differences are more significant at its breakeven production volume.

Table 3.5 Breakeven Points Versus Labor Rates in 1,000 lb

process	\$10.00/hr	\$15.00/hr	\$20.00/hr
automated cutting	88.1	73.0	73.0
robotic transfer	54.1	42.2	35.3
tape layup	37.2	30.6	23.5
filament winding	2.4	2.4	2.4

The cycle times for manual production were based on time studies by Northrop for a simple flat laminate. For a 24 ply 4 square foot laminate, the layup rate is 2.5 lbs per hour. Layup rates quoted in the literature range between .5 [82], 1.0 [83], 1.5 [84] and 3.0 [85] lbs per hour. This discrepancy is due mainly to the manner in which rates are calculated and to differences in part complexity and learning curve. Generally, these rates are based on the production volume over a given period of time instead of direct timing of production tasks. Especially for small volume operations, the production rate will be dependent on organizational efficiency and the flexibility of the workforce. Complex parts produced in small batches will decrease the layup rate significantly.

Figure 3.10 shows a worst case scenario in which the nominal layup rate is increased by a factor of five to account for increased part complexity and smaller batch sizes. It is assumed that the automated rates are unaffected by part complexity and batch size. Comparison with Figure 3.1 shows a significant reduction in breakeven production volumes and a higher percentage reduction in cost. Breakeven points are 5,900, 2,200 and 1,500 parts for automated cutting, robotic transfer and tape layup, respectively. It is, however, unlikely that the automated methods will not experience a similar increase in cycle time. In fact, these methods may not be capable of fabricating many complex parts that skilled labor can fabricate. Since a part designed for automation would probably avoid high levels of complexity, the comparison of simple geometry parts appears to be more accurate.

3.3.4 Sensitivity to Equipment Parameters

As the production rate increases, the equipment costs decrease and the cost is less sensitive to changes in equipment cost and useful life. Figure 3.2 shows that at low production rates, the equipment costs for the machine assisted layup methods represent between 30 and 40% of the total cost. This drops to less than 20% at higher production rates as indicated in Figure 3.6. The sensitivity of the breakpoints to equipment cost and useful life depends on the investment in equipment for manual production and the alternative near the crossover point and the relative slopes of the curves. Table 3.6 gives breakpoints for varying equipment cost. The breakpoint for automated cutting decreases considerably with decreases in equipment cost and increases in useful life. Breakpoints for robotic transfer and tape layup are less sensitive to equipment cost and useful life. The breakpoints for filament winding are only slightly affected.

Table 3.6 Breakeven Points Versus Equipment Cost in 1,000 lb

process	50%	75%	100%
automated cutting	37.6	56.5	73.0
robotic transfer	21.2	30.6	42.4
tape layup	15.8	21.2	30.6
filament winding	2.2	2.2	2.4

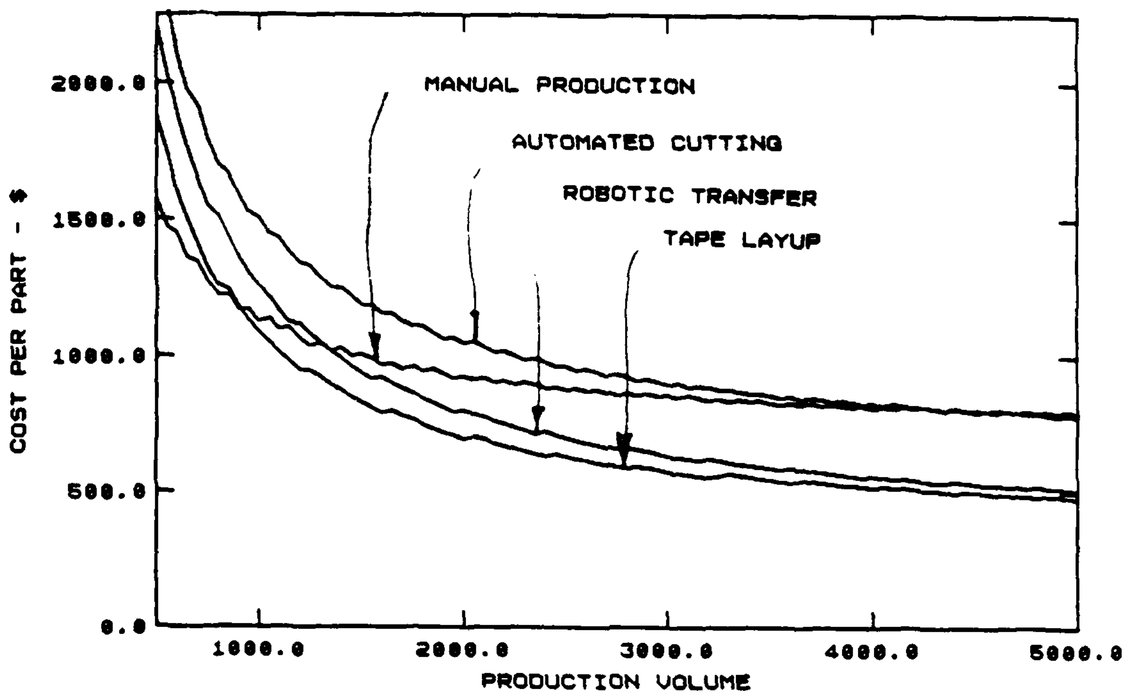


Figure 3.10 Fabrication Costs for Inflated Manual Labor Rate

There is not as direct a correlation between equipment rates and changes in breakeven points and cost. The breakpoints are relatively insensitive to increases in equipment capacity. The sensitivity of cost to equipment rates depends on the percentage of cost associated with equipment and the equipment utilization at a given production volume. The cost at production rates of 5,000 and 25,000 parts per year for equipment rates three times the nominal value were compared. Only filament winding experienced a substantial cost savings with increasing capacity. At the lower production volume, the cost of the other methods did not increase with increasing capacity whereas the cost savings for filament winding techniques range between 12.5 and 16%. At the higher production volume, the cost savings were 3.3%, 1.8%, 12.7% and 13.7% for robotic transfer, pultrusion, filament winding with autoclave cure and filament winding with oven cure, respectively. Increasing the capacity for automated cutting, tape layup and RTM does not affect the cost at either production volume.

3.4 Indirect Costs

Indirect costs are more difficult to quantify than direct costs. Work-in-progress inventory and floor space can be estimated from cycle times and cost information provided by the direct cost model. Indirect labor for manual production is calculated with the labor multipliers presented in Table 2.5. For the alternative methods, reductions in indirect labor are based on ratio of personnel for manual and the alternative method and the ratio of tooling requirements. Scrap and rework costs will be discussed in detail in Section 5. Figure 3.11 shows the direct and indirect costs for a 4 ft^2 24 ply part fabricated at a production rate of 25,000 parts per year and produced in batch sizes of 2,000 parts. A comparison with Figure 3.8 shows that the indirect costs do not affect the relative costs of the alternative processes.

Indirect labor does increase the relative cost of manual production. Automated cutting experiences a similar increase in cost since there is little reduction in personnel or tooling requirements. Robotic transfer, tape layup and filament winding processes reduce indirect labor by reduction in personnel. In this example, since it is assumed that there is no waiting in queues with the exception of the autoclave, the work-in-progress inventory costs can be neglected since cycle times and the value added are low for these processes. The floor space costs, however, do affect the cost effectiveness of the machine assisted prepreg layup methods. The automated prepreg layup methods require more facilities resources than manual production. Pultrusion, RTM and filament winding with oven cure have lower floor space requirements than manual production.

3.5 Summary

The results of the economic analysis indicate that methods such as pultrusion and filament winding which use neat resin and fibers benefit from a substantial materials cost reduction over those methods which utilize prepreg materials. In addition, since these methods generally have lower equipment costs and cycle times, they are able to compete with manual production even without a savings in material costs. Automated prepreg methods are only marginally cost effective for simple flat laminates. These technologies compete by eliminating the need for compaction between plies and reducing the scrap and offer only a 25 to 50% decrease in layup cycle time.

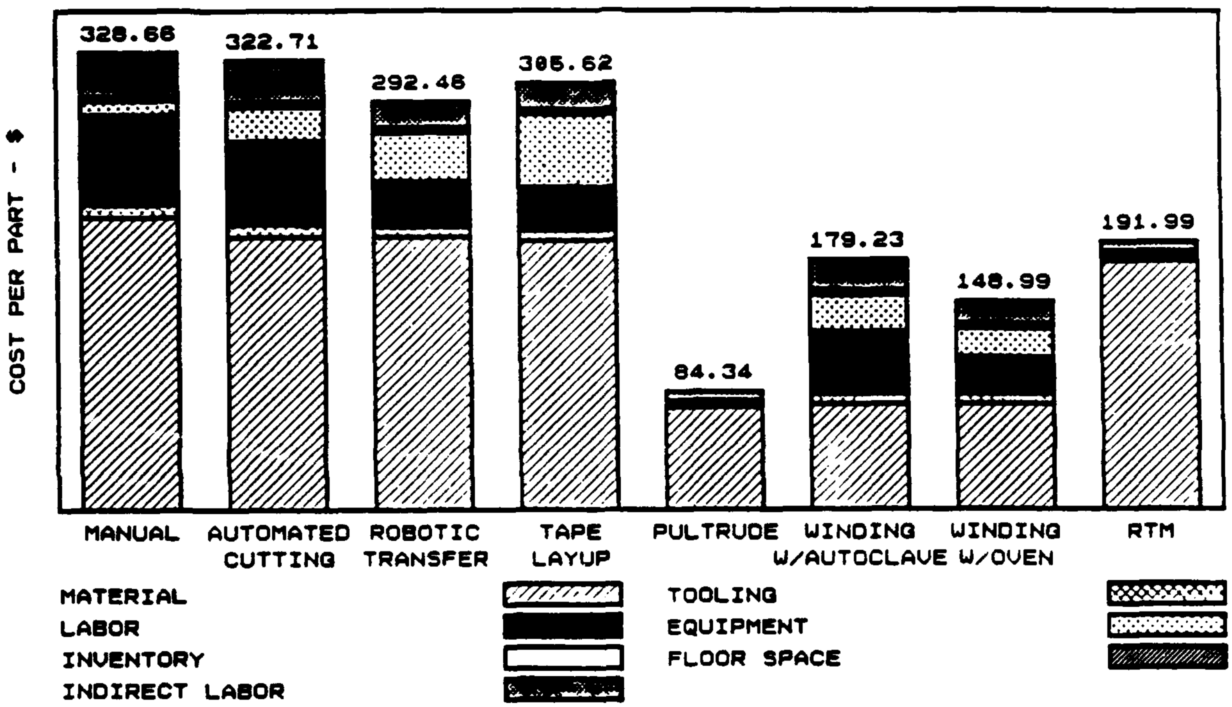


Figure 3.11 Direct and Indirect Costs for a 24 Ply 4.1 lb Laminate

4. FLEXIBILITY ISSUES

4.1 Introduction

There is an inherent tradeoff between equipment utilization and the ability of a firm to respond to random orders. Although low equipment utilization will increase manufacturing costs, it generally will shorten response time and the level of work-in-progress inventory. The optimal operating point for a given firm will depend on its manufacturing strategy. Companies which choose to compete on low cost will maximize equipment utilization; firms which compete on response time will tend to operate below capacity and sacrifice potential cost savings. To quantify the tradeoffs between response time, work-in-progress inventory and manufacturing cost, the response of the manufacturing system is simulated to determine the effect of downtimes and randomly arriving orders on waiting times in queues and equipment utilization. In this section, the system performance of the automated prepreg layup techniques will be compared to manual layup methods. In addition, the effect of batch size on manufacturing cost will be investigated.

4.2 Description of Simulation

A monte carlo simulation program was implemented to estimate the system response to randomly arriving jobs and equipment downtime. The simulation collects data on response time, throughput time, equipment utilization, starvation and blockage and queue statistics including average waiting time and the average and maximum number of parts in the queue. This information was then used with the economic model to determine the effect on manufacturing cost.

The basic system, shown in Figure 4.1, consists of several workstations linked together by queues. Table 2.2 summarizes the tasks performed at each workstation for each method. Parts are queued in order of arrival and each workstation can have multiple machines operating in parallel. If there are multiple parallel machines operating at a workstation, the next part is queued to be processed on the next available machine. If the number of parts in a queue reaches an adjustable limit, the machines in the previous workstation are blocked and cannot accept parts until the number of parts in the queue is reduced. During each simulation run, a random distribution of multiple orders arrived over a predetermined period.

4.3 Performance Measures

Statistics were collected from the arrival of the first order to the completion of the final part. The performance measures included equipment utilization, response time and throughput time. Equipment utilization and throughput time were used to calculate the manufacturing cost.

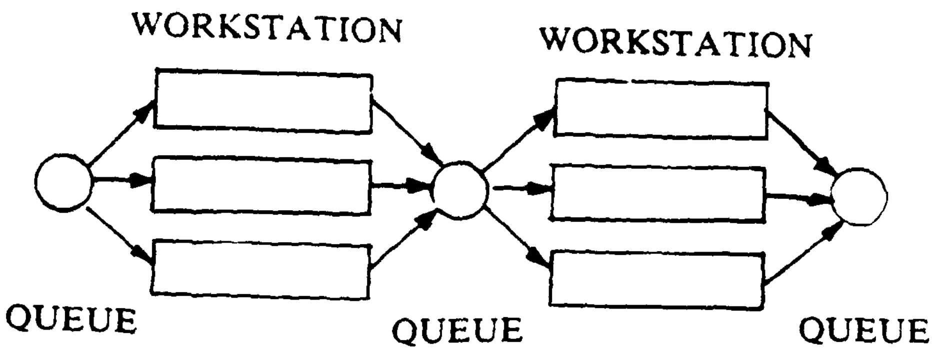


Figure 4.1 Schematic of Simulation System

4.3.1 Equipment Utilization

The system software records the percentage of time that the equipment in each workstation is down, starved or blocked. Starvation refers to an equipment state in which the equipment is available for operation but there are no parts in the queue. A machine is blocked if it is available for operation but the queue for the next workstation is full. The equipment utilization was used to determine an annual production rate needed to calculate the manufacturing cost.

4.3.2 Response Time

The response time, which is the elapsed time between arrival of the order and completion of the part, includes the wait at each queue and the cycle time at each workstation. The magnitude of the response time is a function of downtime statistics, order size and frequency of arrival. Near capacity production rates and high equipment utilization result in long response times. Small frequent evenly spaced orders minimize the response time without sacrificing production rate.

The minimum response time is given by the expression

$$t_{r_{min}} = \frac{N_o\, t_{c_j}}{2\, M_j} + \sum_{i=j}^{N} t_{c_i} + t_{c_N}/2 \tag{4.1}$$

where j is the workstation with the slowest production rate, t_c is the cycle time, N_o is the number in the order and M_j is the number of machines at that workstation and $M_j < N_o$. The first term is the minimum wait in the queues and the last term is the minimum wait in the autoclave queue. Although the response time is minimized as the number of machines approach the number of parts per order, additional parallel equipment can drastically increase the cost. In some cases, however, the incremental cost of adding a machine or laborer to a bottlenecked workstation may be justified by a large decrease in response time.

4.3.3 Throughput Time

The throughput time is the elapsed time from the start of processing until completion of the part. The minimum throughput time is given by

$$t_{t_{min}} = \sum_{i=j}^{N} t_{c_i} + t_{c_N}/2 \tag{4.2}$$

By limiting the number of parts in selective queues, the throughput time of the system can frequently be reduced without sacrificing productivity. Figures 4.2 and 4.3 show production rates and throughput times, respectively, for varying limits on the second queue for a 1-1-1 layout of tape layup. Although decreasing the queue limit below 15 results in lower throughput times, it reduces the production rate. In the results section, queue limits were chosen to minimize the throughput time without reducing the production rate by more than 5%.

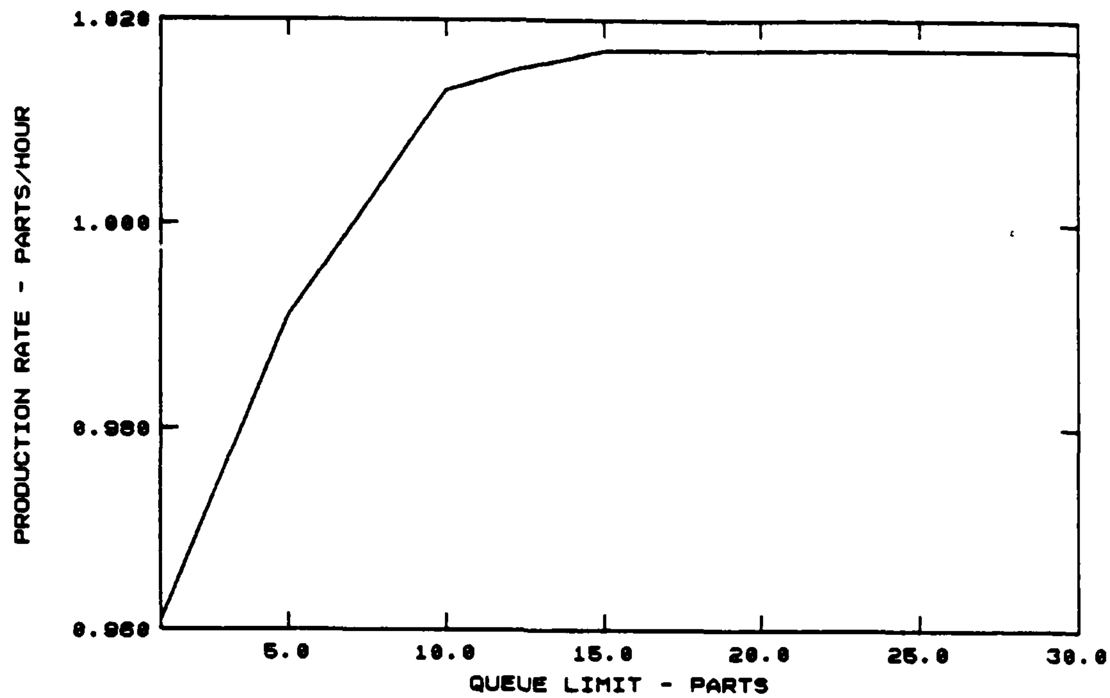


Figure 4.2 Effect of Queue Limits on Production Rate

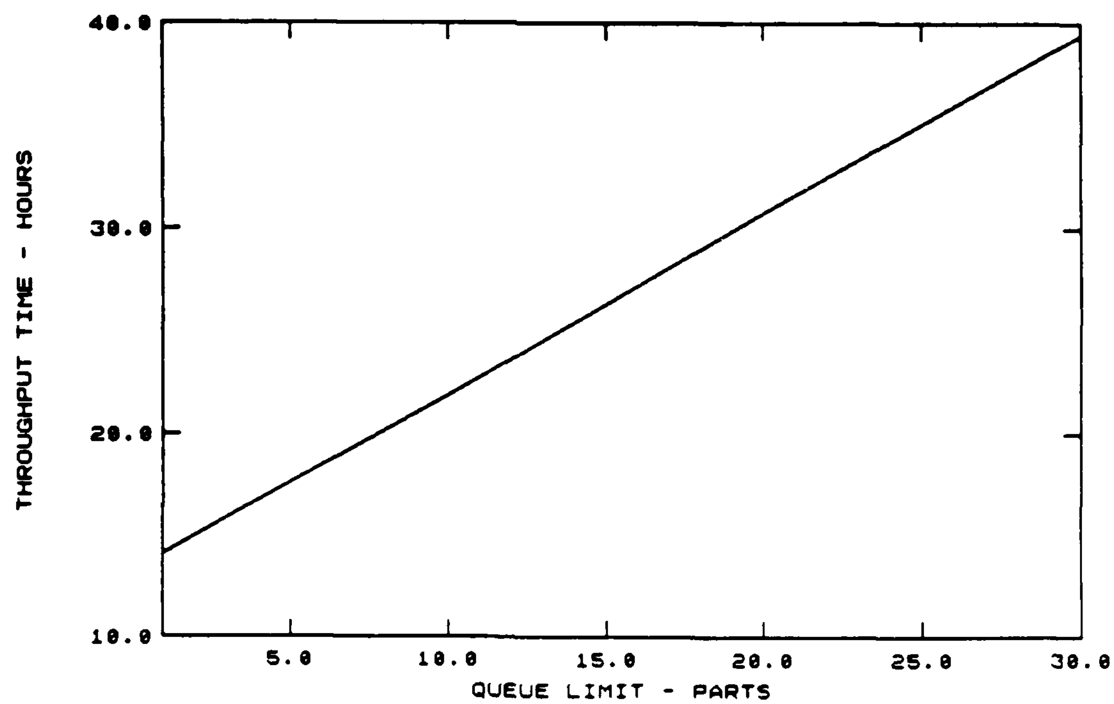


Figure 4.3 Effect of Queue Limits on Throughput Time

4.4 Simulation Results

The simulation was used to compare the response time, throughput time and manufacturing cost of the machine assisted prepreg layup methods to manual production. Multiple orders of fifty parts arrived in a random distribution over a four week period. The number of orders was varied to simulate the effect of varying demand on the system. The part geometry and size was identical to that in the nominal case in Section 3. The cycle times for each workstation are summarized in Table 4.1 for different lot sizes.

Table 4.1 Cycle Times in Hours

work station	lot size	manual	automated cutting	robotic transfer	tape layup
	100	19.45	.05	.05	.61
1	500	5.95	.05	.05	.61
	> 1200	3.08	.05	.05	.61
	100	6.29	15.78	.34	6.29
2	500	1.92	4.82	.34	1.92
	> 1200	.99	2.5	.34	.99
	100	6.0	6.29	6.29	6.0
3	500	6.0	1.92	1.92	6.0
	> 1200	6.0	.99	.99	6.0
	100	-	6.0	6.0	-
4	500	-	6.0	6.0	-
	> 1200	-	6.0	6.0	-

Since actual equipment and manual labor downtime statistics were unavailable, three failure scenarios were used in the simulation studies. The number of failures and the downtime duration and standard deviation for these cases are summarized in Table 4.2. In each case, the failures were randomly distributed over five weeks of operation and the duration represents a gaussian distribution. For the nominal case, Case II, equipment is down 10% of operating time and manual labor is unavailable 5% of the time. The downtime for manual operation were based on personal time used in computation of labor rates. Case I and III were chosen to represent a 50% decrease and 100% increase in downtime for the nominal case.

Table 4.2 Downtime Statistics

		number of failures	duration hours	standard deviation
Case I	equipment	6	4.8	1.43
	manual	7	2.0	.70
Case II	equipment	8	7.2	2.00
	manual	10	2.8	.50
Case III	equipment	11	10.5	2.80
	manual	14	4.0	.70

4.4.1 Optimal Autoclave Capacity

The processing rate of the autoclave is dependent on its capacity. Figures 4.4 and 4.5 show production rate and response time, respectively, versus autoclave capacity for tape layup with one machine per workstation. As the capacity increases the production rate increases until it reaches a maximum around 10 parts and levels off. The response time decreases with increasing capacity until it reaches this optimal operating point and then begins to increase again. If the capacity is too high, the autoclave is idle while waiting for parts and the response time increases. If the capacity is too low, the autoclave workstation will be the bottleneck and will limit the system production rate and increase the response time.

Table 4.3 summarizes the optimal autoclave capacity for each process and a few machine layouts. The machine layout i-j-k means that there are i, j and k machines at the first second and third workstations, respectively. The results show that the optimal autoclave capacity is achieved by matching the throughput of the autoclave to that of the weakest link of the system. For these machine layouts, the capacities are below the potential capacity for a typical size autoclave.

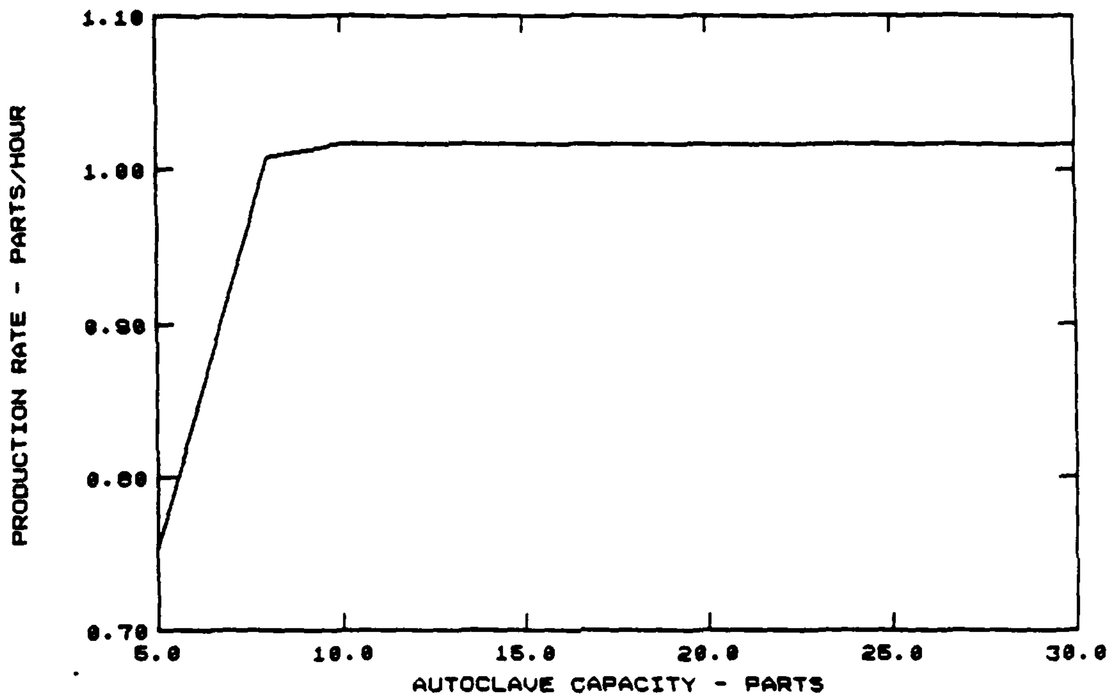


Figure 4.4 Effect of Autoclave Capacity on Production Rate

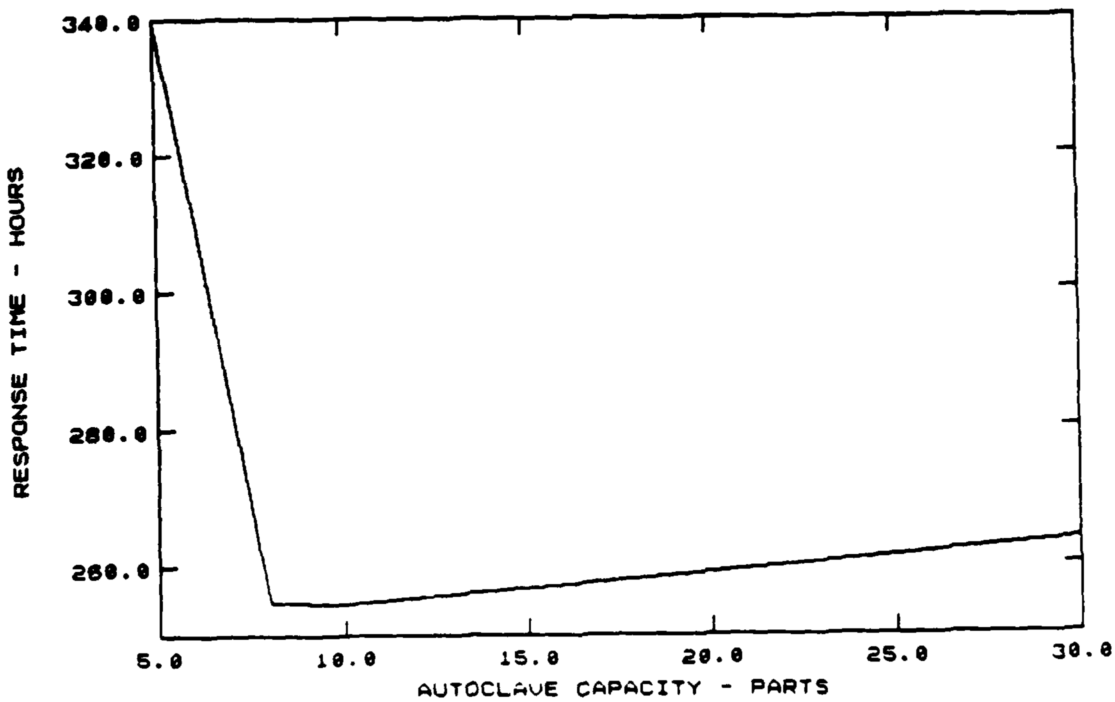


Figure 4.5 Effect of Autoclave Capacity on Response Time

Table 4.3 Optimal Autoclave Capacity

process	layout	maximum annual production volume parts	autoclave capacity parts
	1-1-1	2,148	5
manual	2-1-1	4,308	8
	4-2-1	7,188	15
automated cutting	1-1-1-1	2,838	5
	1-2-1-1	5,514	10
	1-4-2-1	11,148	20
robotic transfer	1-1-1-1	5,640	10
	1-1-2-1	9,228	20
	1-2-4-1	18,474	40
tape layup	1-1-1	5,706	10
	1-2-1	9,504	20
	2-3-1	12,690	25

4.4.2 Response Time

The response time of an unbalanced manufacturing line is limited by the workstation with the highest cycle time. Table 4.1 indicates that there is a substantial mismatch in processing rates between stations when only one machine operates at each workstation for each of these methods. This is especially true for methods which use the automated cutting systems and for manual methods when lot sizes are small. More balanced operation can be achieved by using multiple machines at some of the workstations. This added capacity will decrease response time and work-in-progress inventory and decrease manufacturing cost if demand increases. Adjusting the capacity of the autoclave reduces the mismatch in processing rates for this station.

Figure 4.6 shows the minimum response time versus order size for each method. Increasing the order size leads to a linear increase in the waiting time in the queues. For infrequent orders and equipment failures, the values in this figure are close to actual response times of the systems. Due to their higher cycle times, the slopes of the manual production and automated cutting methods are steeper and the response times are longer. As the frequency of the orders and failures increase, it is necessary to simulate the system to predict the response time. Table 4.4 summarizes the minimum response times for each method and layout for an order size of fifty parts.

Figures 4.7, 4.8, 4.9 and 4.10 compare the response time versus manufacturing cost for each method for several machine layouts as the production rates and downtime statistics vary. Layouts with one machine per workstation have very high response times and are only capable of producing rather low production volumes. For this type of layout, the response time is very sensitive to the production volume; small decreases in volume drastically decrease the response time and increase the cost. Manual production

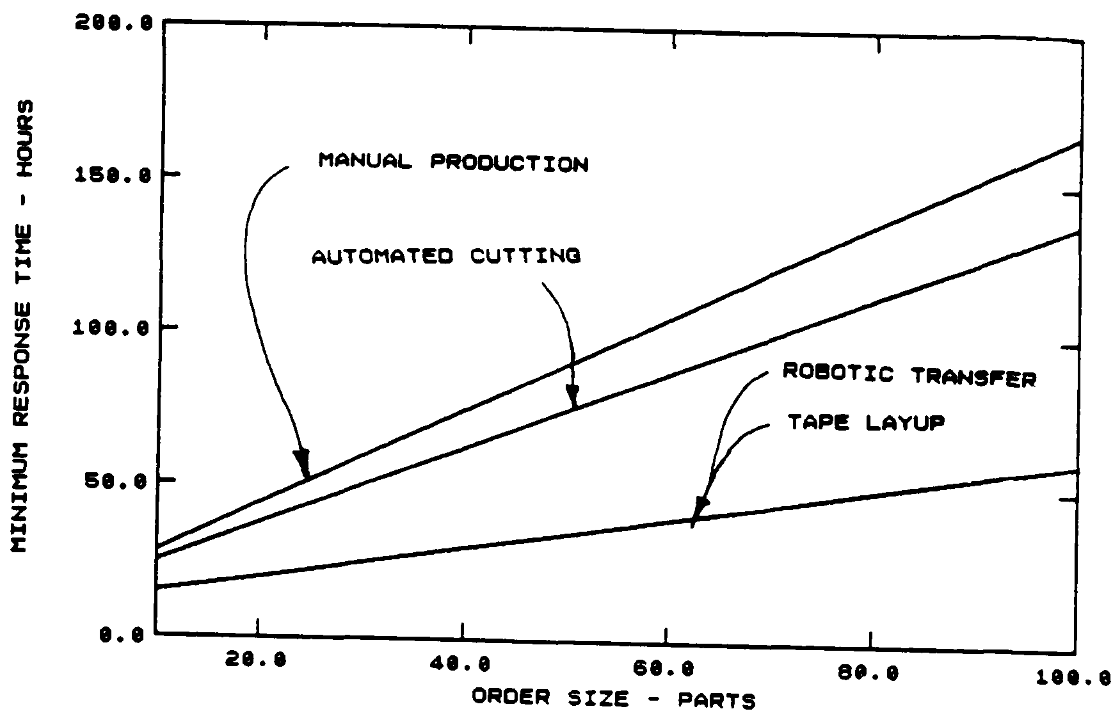


Figure 4.6 Effect of Order Size on Response Time

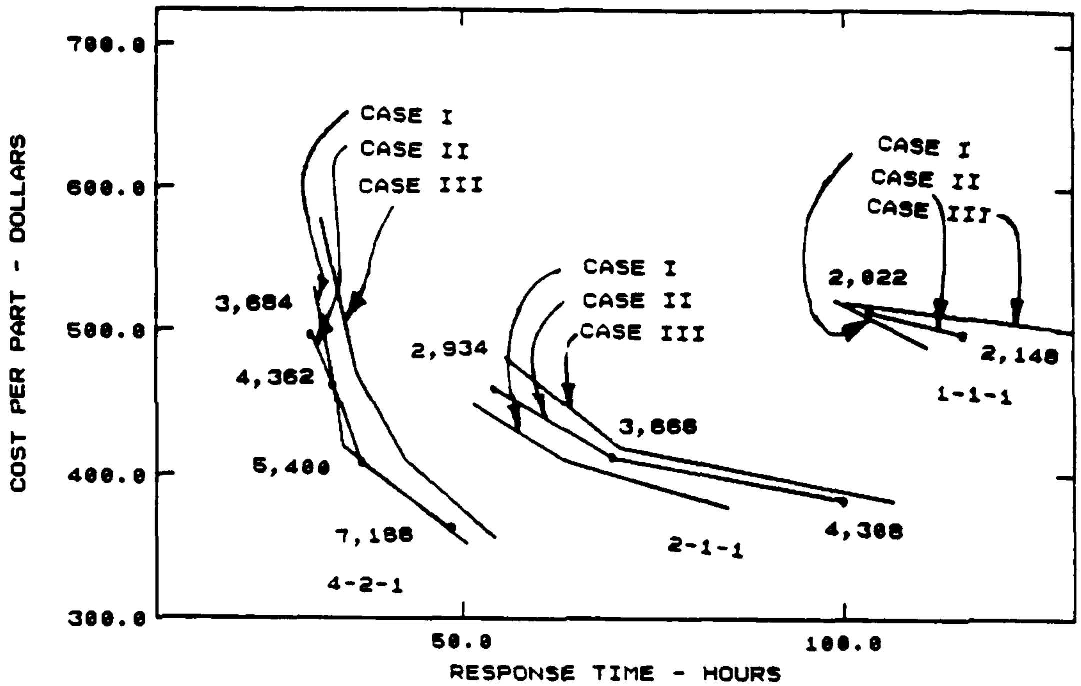


Figure 4.7 Cost-Response Tradeoff for Manual Production

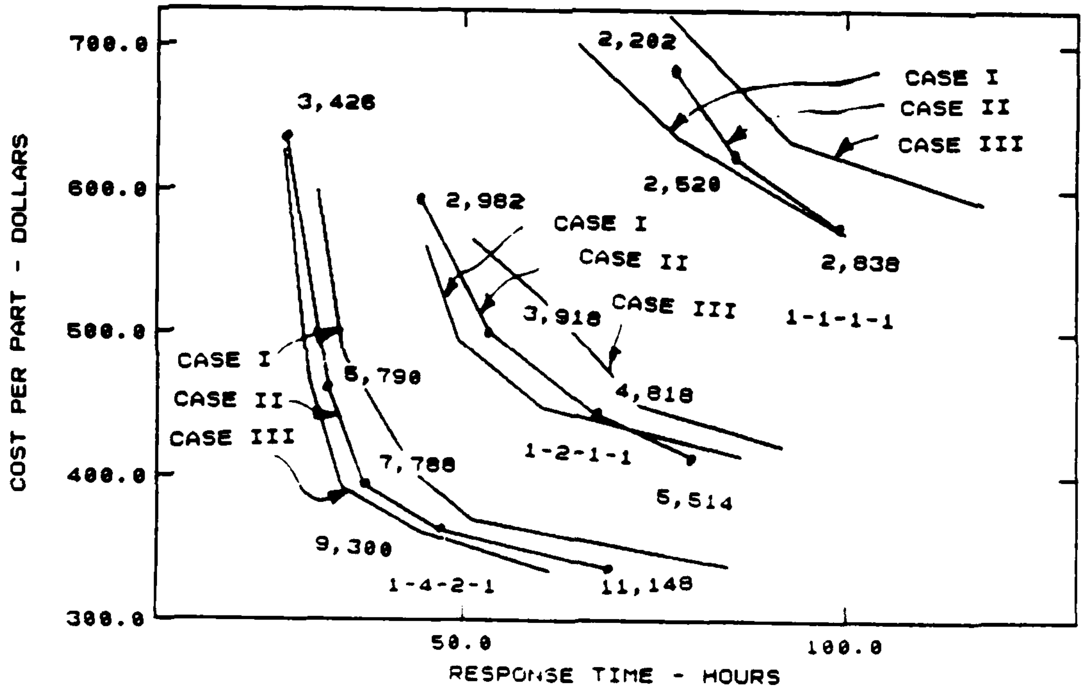


Figure 4.8 Cost-Response Tradeoff for Automated Cutting

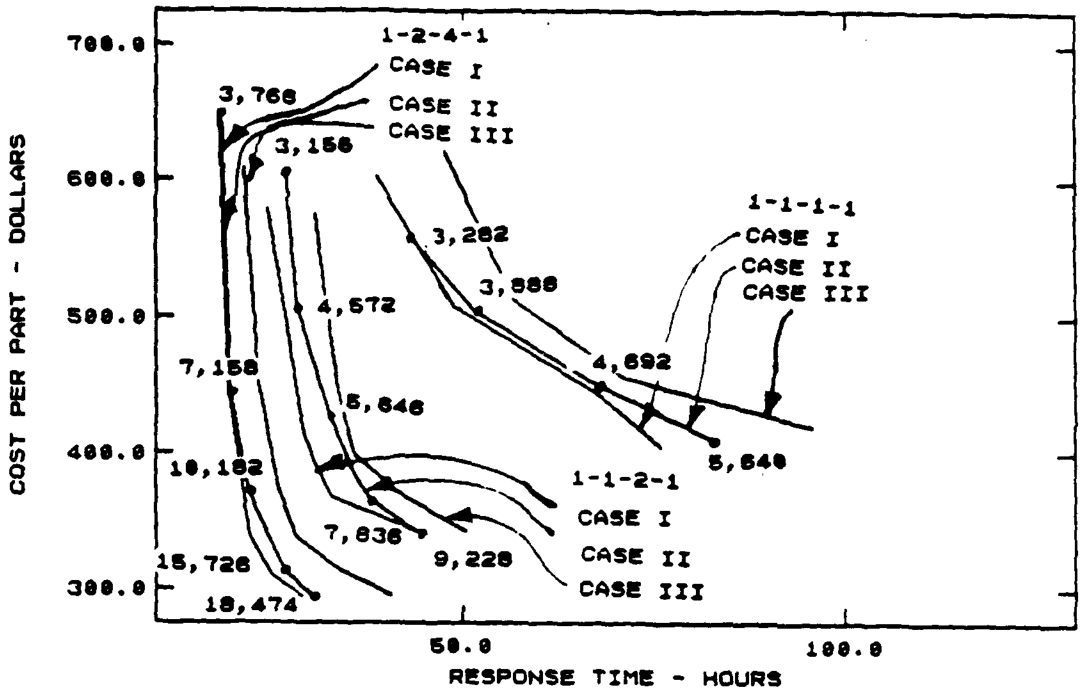


Figure 4.9 Cost-Response Tradeoff for Robotic Transfer

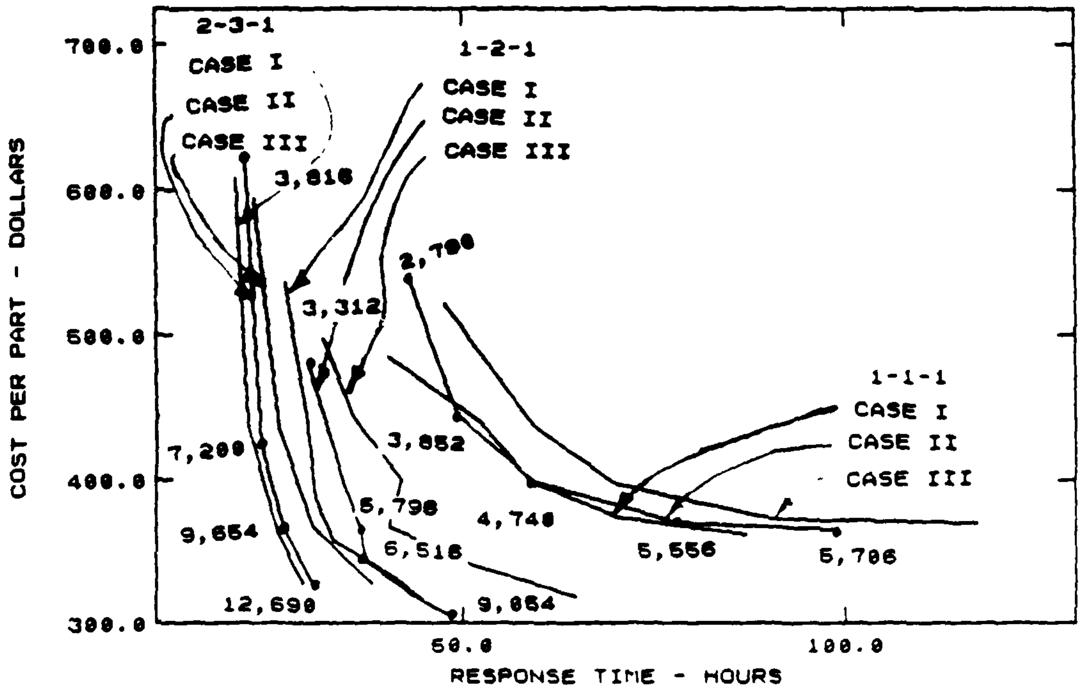


Figure 4.10 Cost-Response Tradeoff for Tape Layup

experiences a less severe increase in cost than the alternative methods since at these production volumes the labor costs are less than equipment costs.

Table 4.4 Minimum Response Times

method	layout	response time - hours
manual production	1-1-1	90.07
	2-1-1	51.57
	4-2-1	25.44
automated cutting	1-1-1-1	75.04
	1-2-1-1	43.79
	1-4-2-1	28.16
robotic transfer	1-1-1-1	35.13
	1-1-2-1	22.75
	1-2-4-1	16.57
tape layup	1-1-1	35.35
	1-2-1	25.85
	2-3-1	18.85

Increasing the number of laborers at the layup and autoclave prep workstations results in large decrease in response time and significant cost increases for a given production volume. Once enough workers and equipment have been added to each workstation to balance the line, increasing the capacity of any one workstation will not decrease response time. When the workstations are balanced, the response time versus manufacturing cost curve is very steep since the response time is very sensitive to production volume but the cost increases dramatically with decreasing demand. Since a large price is paid for a minimal improvement in response time, operating below capacity does not offer much of a competitive edge in this case.

A comparison of the different methods shows that the alternative methods decrease the cycle time and therefore the response time. The addition of an automated cutting system to hand layup operations results in a large decrease in response time combined with a large increase in cost. If multiple laborers are used at the layup and autoclave prep stations, the decrease in response time is less dramatic but the cost increase is still substantial. The use of transfer robots results in lower response times, but larger production volumes are necessary to compete on a cost basis. When multiple transfer robots and laborers preparing parts for cure are used, the response time diminishes but the cost is prohibitive at low production volumes. Only tape layup offers a substantial decrease in response time, primarily due to decreased cycle time, without large increases in cost at lower production volumes. At high production volumes, robotic transfer and automated tape layup offer similar reductions in response time at low cost.

4.4.3 Throughput Time

The throughput time, shown in Figures 4.11, 4.12, 4.13 and 4.14, is a function of the equipment utilization and the autoclave capacity. Table 4.5 gives the minimum throughput time for each alternative method. The simulated values for manual production are very close to the predicted minimum values. For the alternative methods, however, the throughput times are much higher than the minimum values. This is related to choice of autoclave capacity. At high production volumes, the throughput times are nearly double the minimum, since the queue is seldom empty when new parts arrive. Since the autoclave capacity was chosen to optimize response time at maximum production volumes, at low volumes the throughput times and response times will increase since the autoclave will be waiting for the correct number of parts before beginning a new batch. When the equipment is operating below capacity, it may be possible to minimize the throughput time further by reducing the number of parts in the autoclave.

Table 4.5 Minimum Throughput Times

method	throughput time - hours
manual production	13.07
automated cutting	12.54
robotic transfer	10.38
tape layup	10.60

4.4.4 Individual Heated Tools

Since the wait in the autoclave queue can add to the response and throughput times and the optimal capacity is in some cases quite low, the use of individual heated tools to replace the autoclave was investigated. When each layout is operating at its maximum capacity, the response times are almost identical since the autoclave capacity matches the capacity of the weakest link. As the production volume decreases for each layout, the response time is slightly lower for the system with individual tools since the wait for the autoclave has been eliminated. Comparison of Figure 4.14 to Figure 4.15 shows the decrease in throughput times when individual tools are used. There may also be a cost savings since a substantial investment in tooling could be made to offset the 1.2 million dollar investment in the autoclave.

4.5 Direct Costs for Batch Production

The major use of advanced composites today is for aerospace applications. Since lot sizes are small in this industry, it is important to consider the costs associated with the learning curve, reprogramming, setup and retooling. As batch sizes become smaller, the learning curve results in significantly longer average cycle times and possible increases in labor force and equipment needs. Reprogramming and setup times are very dependent on part complexity, the type of CAD/CAM interface and features of particular equipment used. It is assumed that the machine assisted layup methods are interfaced with a CAD

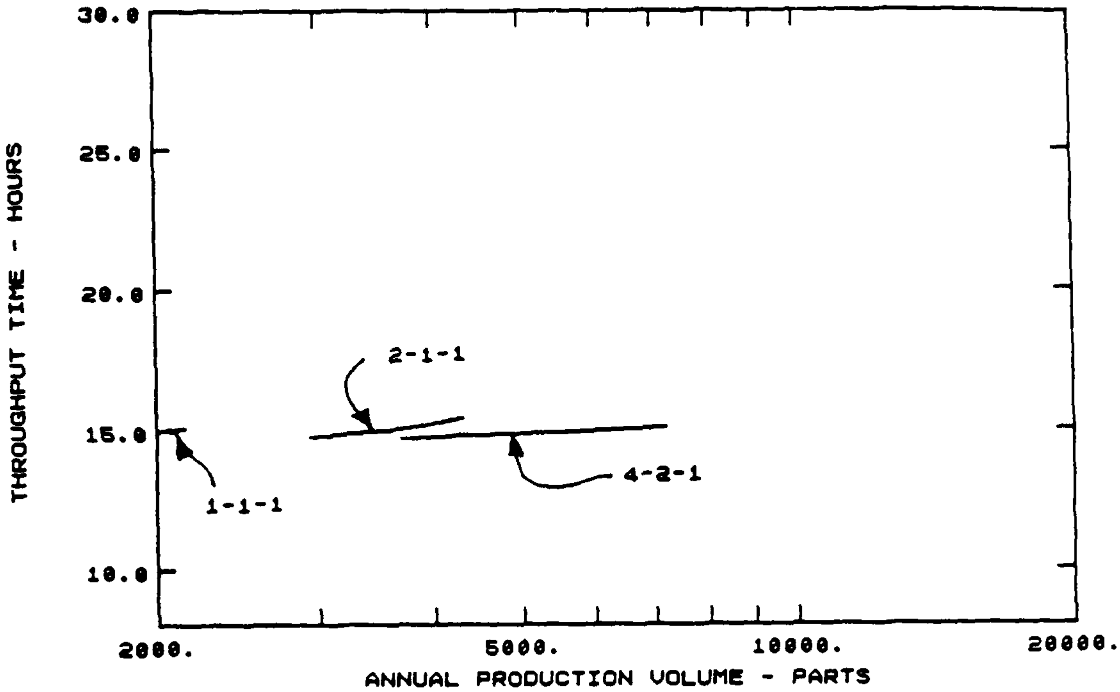


Figure 4.11 Throughput Time for Manual Production

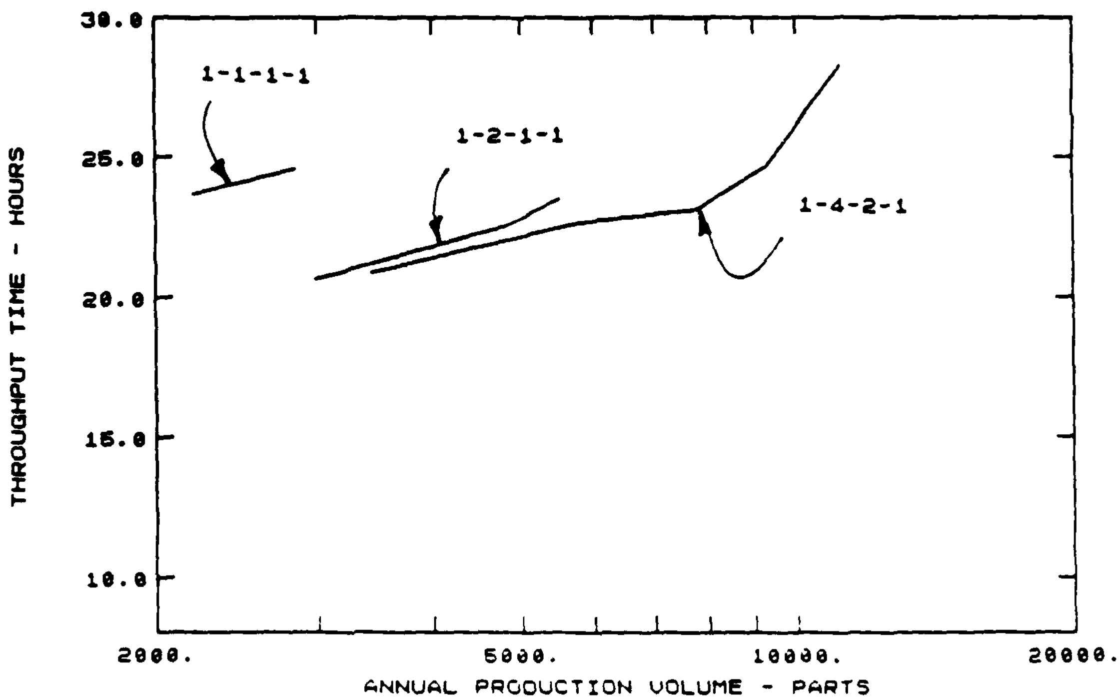


Figure 4.12 Throughput Time for Automated Cutting

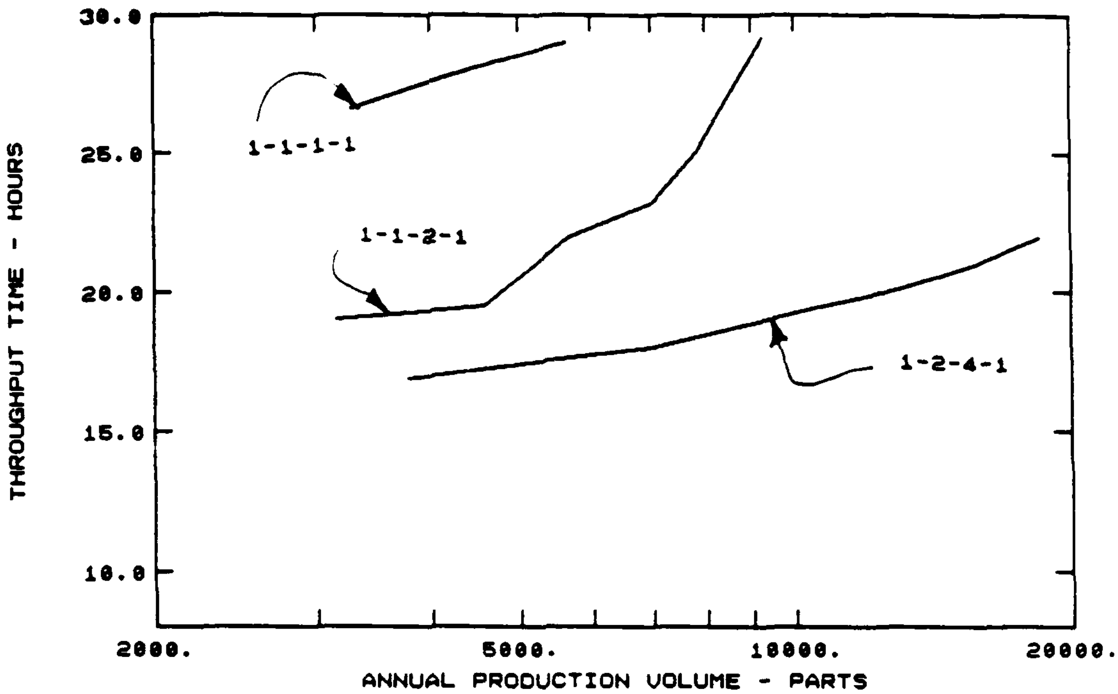


Figure 4.13 Throughput Time for Robotic Transfer

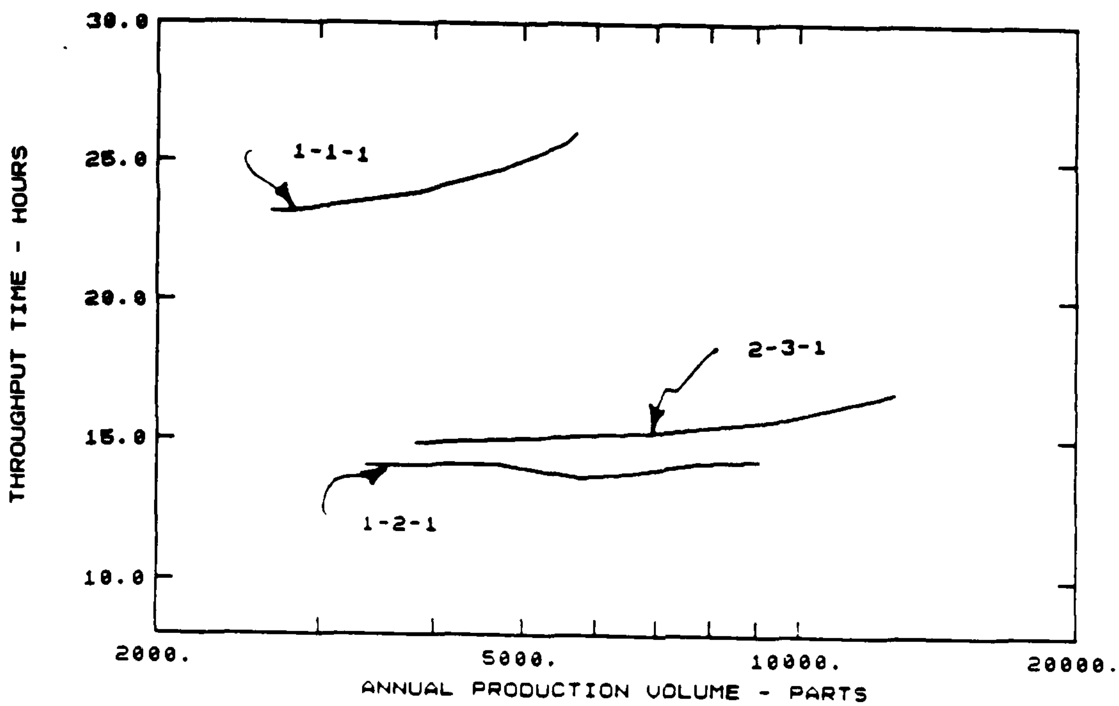


Figure 4.14 Throughput Time for Tape Layup

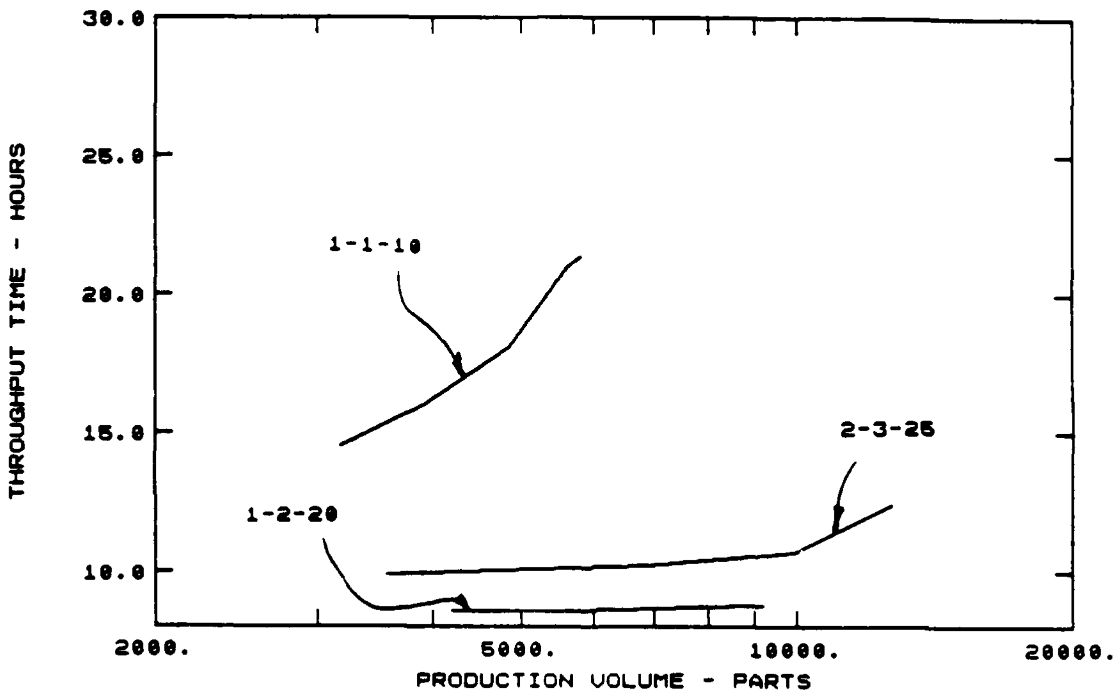


Figure 4.15 Throughput Time for Tape Layup with Individual Tools

system and that the reprogramming and setup times can be neglected. For pultrusion, the setup time is a function of the number of tows and complexity of the shape. Setup times for filament winding and pultrusion were 16 hours and 8 hours, respectively. These values are conservative and were based on discussions with industry.

Figure 4.16 shows the change in cycle time as batch sizes increase from 20 to 1220 parts. Methods with the highest degree of manual labor experience the most dramatic change in cycle time as batch size varies. The cycle time for manual production decreases by 85%. Figure 4.17 shows the manufacturing cost for a 4 ft^2, 4.1 lb part for an annual production volume of 15,000 parts for varying batch sizes and a 50% learning retention. The decrease in cost for manual production and automated cutting systems is nearly an order of magnitude as batch sizes increase from 10 parts to 1000 parts. Robotic transfer, tape layup, and filament winding experience cost reductions in proportion to their manual labor content of 57.5%, 54.9%, and 71.7%, respectively. The reduction in cost for filament winding with oven cure and pultrusion is due to the decreasing effect of setup times on the cost and unrelated to the learning curve. The setup time has little influence on part cost for batches greater than 50 and 150 parts for filament winding and pultrusion, respectively.

The breakeven points are also affected by the batch size assuming a 50% learning retention. Figure 4.18 shows the breakeven production volumes versus batch size. Breakeven points for automated cutting, robotic transfer and tape layup decrease by 92%, 96% and 95.7%, respectively, as batch sizes decrease from 600 to 10 parts. As batch size decreases, the manual cycle time increases while the automated cycle time is constant. The additional equipment expense is overcome by labor reduction. Filament winding experiences only a slight decrease in breakeven points for batch sizes less than 400 parts.

4.6 Summary

Each of the alternative methods reduce the cycle time and therefore the throughput of the system and the work-in-progress inventory costs. For the machine assisted prepreg layup methods, there is a substantial mismatch in the capacities of workstations resulting in a bottleneck at the "slowest" workstation which dominates the response time. Operating below capacity does not offer a competitive edge, since decreases in equipment utilization results in large cost increases and only marginal gains in response time. Autoclave capacities which optimize response time are low in comparison to the size of the typical autoclave. The use of individual heated tools would reduce response time by eliminating the wait in the autoclave queue and possibly the labor intensive autoclave preparation and compaction procedures.

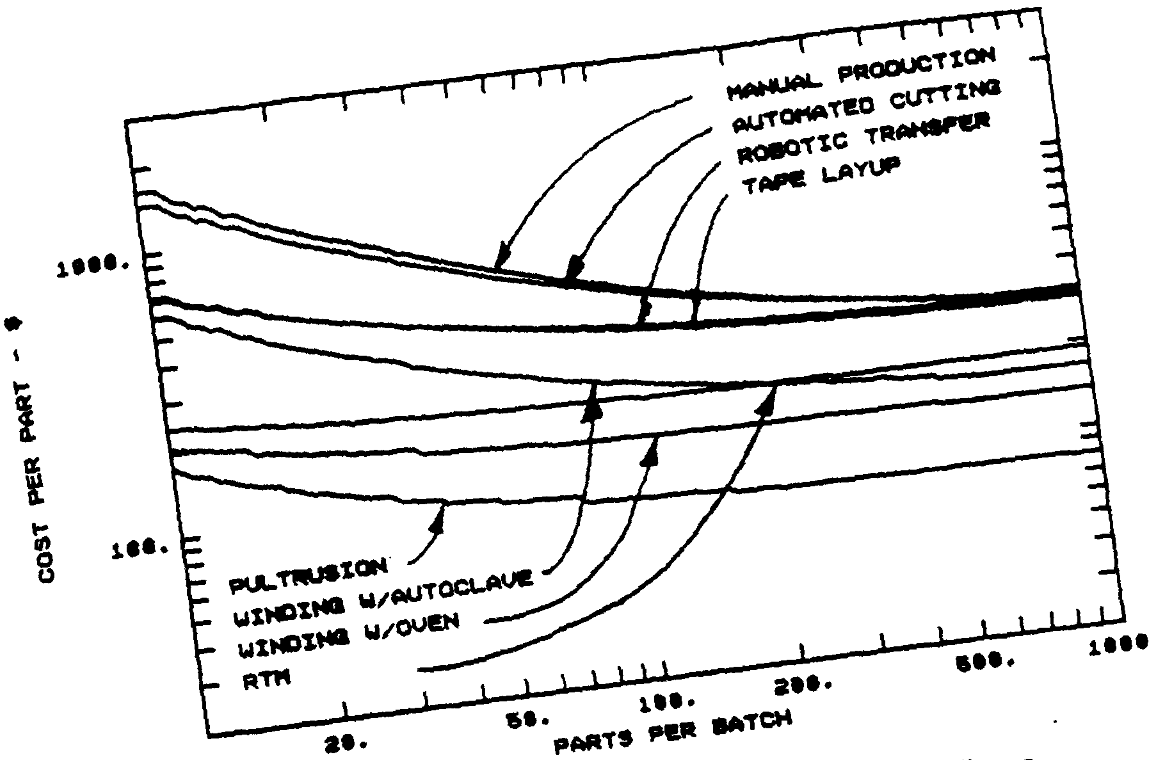


Figure 4.16 Effect of Batch Size on Cycle Times

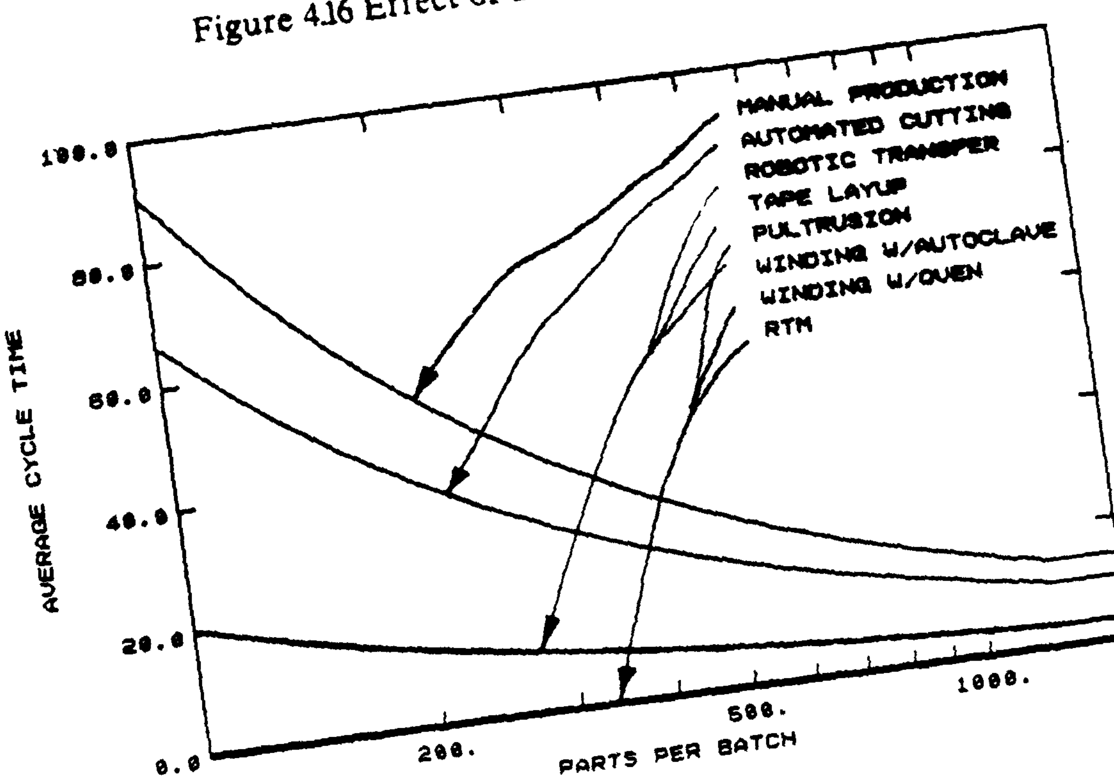


Figure 4.17 Effect of Batch Size on Part Cost

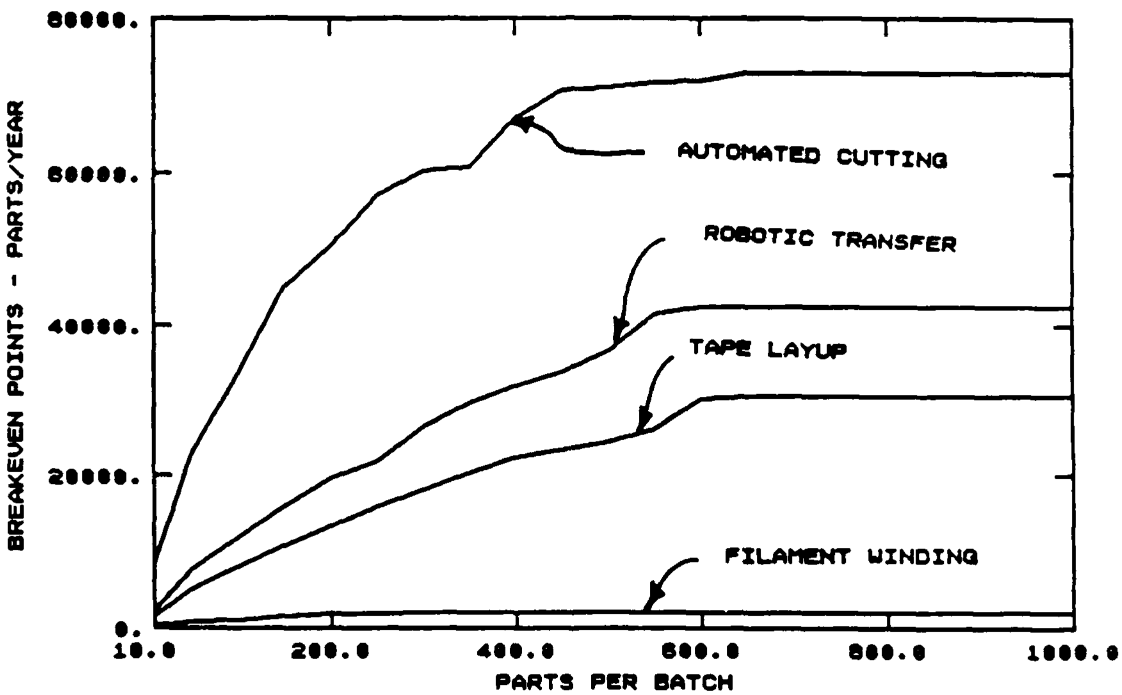


Figure 4.18 Effect of Batch Size on Breakeven Points

5. Quality Issues

5.1 Introduction

In a recent survey of the reinforced plastics/composites industry [86], 64% of the surveyees viewed quality as the most important issue facing the industry today. Most felt that high quality is important for companies to maintain a competitive edge over alternative materials. The majority also noted that having a high quality product is often the deciding factor in product acceptance and keeping satisfied customers. Although improvements in product quality reduce rework and scrap costs, potential increases in market share may provide a more beneficial incentive. It is, however, difficult to quantify the relative quality of alternative methods and the indirect benefits of quality improvements.

According to Ishikawa [87], the true quality of a product is related to its ability to satisfy the customer's requirements. Since true quality is difficult to measure, substitute quality characteristics, which can be related to true quality by quality analysis and through statistics, are generally used. In this section, a framework based on control theory for evaluating process quality in terms of process variability and limitations will be presented. The relative substitute quality characteristics and sources of error which reduce quality or prohibit the production of consistent quality parts for each alternative method will be identified. Examples will be used to show the effect of microstructure and cost and the use of process models to identify limitations and quantify variability.

5.2 Problem Formulation

The quality problem can be formulated as a control problem as shown schematically in Figure 5.1. Although the manufacturer would like to control the true quality of the part, it is only possible to measure the microscopic process outputs or the substitute quality characteristics. Inability to control a process results in inconsistent product quality and inhibits automation. This process variability decreases the flexibility by increasing setup times since more time is required to adjust system parameters to produce consistent quality parts each time processing conditions change. The trend would be to produce larger batch sizes to reduce the average setup time per part.

5.2.1 Process Inputs and Outputs

The inputs to the system are the process parameters such as pressure, temperature, equipment positions and rates and human abilities which the manufacturer would like to control in order to produce consistent quality parts. The process outputs listed in Table 5.1 can be thought of as microscopic properties which affect the product properties and dimensions and, depending on the user's requirements, the true quality of the part. Limitations on these outputs due to physical constraints on the process affect the level and consistency of quality and the ability of the process to respond to variations in processing parameters. The outputs of the process can be used to define substitute quality characteristics, such as material strength, surface quality and tolerances, which

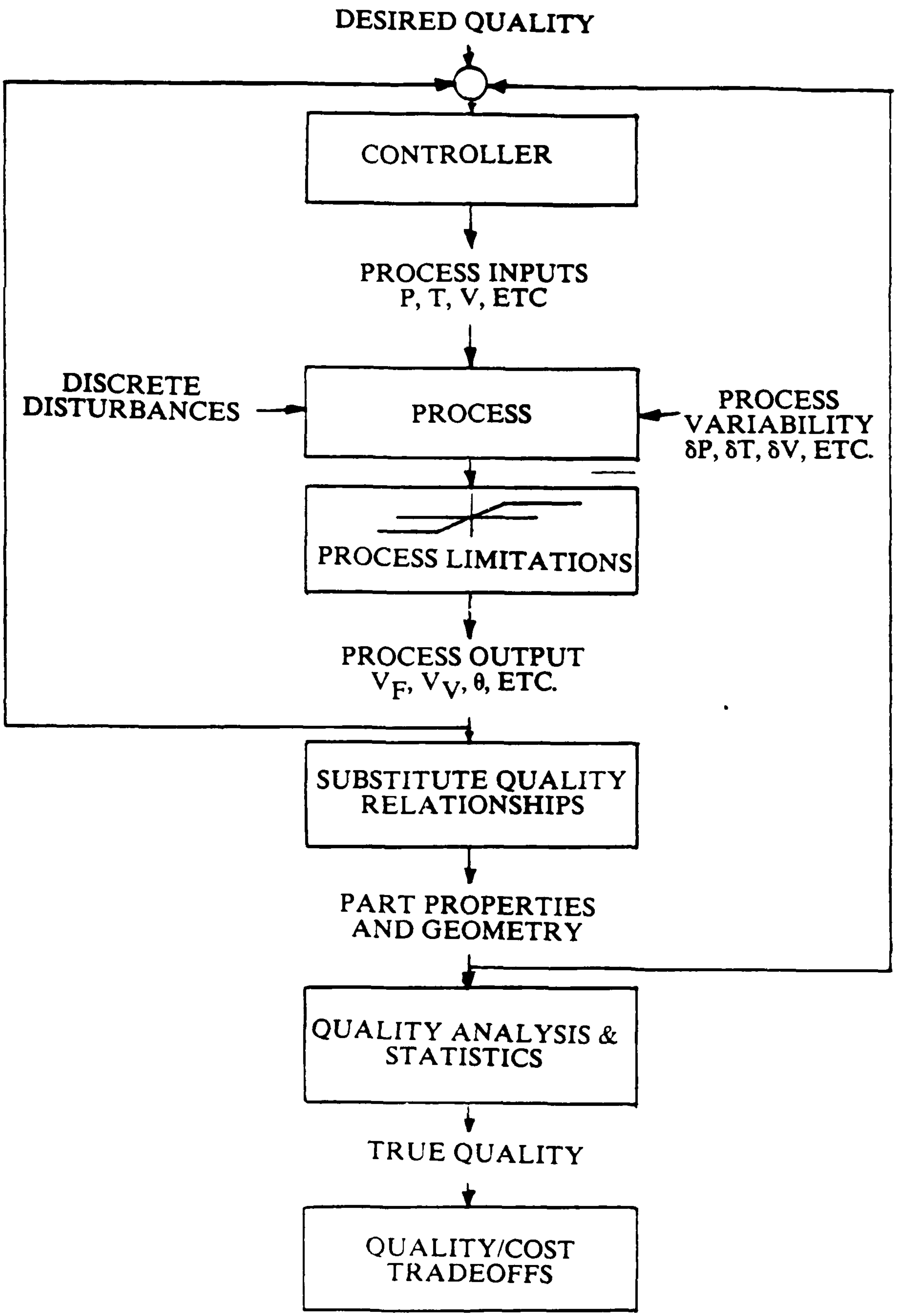


Figure 5.1 Schematic of Quality Problem

can be related to customer satisfaction. Generally, high fiber volume fractions, full degree of cure and low void content maximize the strength of the part. For some processes, however, these outputs may conflict with a user requirement to produce high surface quality or a given geometry.

Table 5.1 Process Outputs

fiber volume fraction	degree of cure
fiber misalignment	damaged fibers
thickness variation	density variation
voids	porosity
fracture	delamination
contamination	degree of moisture

Statistical data or knowledge of process physics can be used to determine the input/output relationships. Most of these processes, however, are very highly coupled systems and the current understanding of these processes varies. The consolidation of laminates has been modeled by several authors including [88, 89, 90]. Pultrusion, filament winding and RTM have been modeled by [91, 92, 93, 94], [95, 96], and [97, 98], respectively. These models predict part geometry parameters such as thickness and fiber volume fraction and can be combined with other models to predict void formation. Using available process models, the response of the system to process variability and process limitations can be evaluated.

5.2.2 Process Errors

Process errors are frequently due to variability in input and process parameters such as human skill, equipment rates and accuracies, and materials properties, such as prepreg tack, resin viscosity, and fiber form density. A high quality process can compensate for variability, although the highly coupled nature of the many of these systems complicates the control problem. In manual production, multiple layers of inspection can be viewed as a crude control system which detects errors after a task is performed and attempts to compensate by rework and adjusting parameters to prevent future errors. Discrete events such as failing to remove backing paper, bag breakage and wrinkling can be evaluated by the use of human reliability models and equipment failure statistics.

The quality of a manually produced part is subject to the skill of the laborer. Due to the complex and tedious nature of the layup process, there are many opportunities for error including missing or extra plies, incorrect fiber orientation, and failure to remove the prepreg backing paper and variability due to differences in human skill and fatigue. These errors can lead to a loss of strength or ply warpage due to asymmetry. There are also several potential sources of error related to the autoclave cure process including part warpage due to uneven heating and cooling, part damage during tool removal and vacuum bag breakage. An advantage of the autoclave processes are low void content and high fiber volume fractions resulting in favorable overall material properties.

Automated cutting systems can also be sources of errors. Reciprocating knives cannot cut boron/epoxy, waterjet systems may cause water absorption by the prepreg material and laser systems may cause edges to bond. Tape layup and robotic transfer devices have problems with gap sizes, restraints on maximum contours and limitations on the ply geometry. The minimum dimension of the part is limited by either the tape width or the grid size of the robotic transfer vacuum system. The variability in prepreg tack and surface characteristics can lead to springback problems during tape layup [99]. These alternative layup techniques, also, face the same autoclave related problems as manual production.

Current pultruded composites structures are limited to constant cross sections and limited fiber orientation. Although roving techniques are restricted to unidirectional fiber orientation, they are low in void content and have high fiber volume fractions. Multidirectional parts can be produced with mat, but this results in higher raw material costs and lower fiber volume fractions. Epoxy systems have problems with die adherence and longer time to gelation and cure resulting in higher pulling forces and possible fiber breakage and poor surface quality [100]. For a 60% fiber volume fraction, flexural and shear moduli and torsional shear strengths were similar to that of parts produced by wet layup, but the interlaminar and flexural strengths were slightly lower possibly due to voids [101].

Filament winding is limited in geometry and fiber structure. Current technology permits winding on any shape of mandrel which does not contain a concave surface. Flat parts, which may not appear windable, may be produced by slitting the part from mandrel before cure. The wound layers are either one 90° layer or helical layers which are effectively two layers thick since plus and minus directions are concurrently wound. Fiber placement must be accurate to prevent gaps between fiber bands. There are potential problems when one fiber is wound over the previous fiber creating predeformations during helical winding affecting structural properties [102]. The major disadvantage of filament winding appears to be higher void content and lower fiber volume fractions than pultrusion and prepreg layup methods.

In RTM, there is an inherent tradeoff between moldability and fiber volume fraction. As fiber volume increases, the permeability decreases increasing filltime and the possibility of premature gelling and nofills. Frequently, it is difficult to individually encapsulate woven roving fibers with matrix because they are so tightly held in bundles. Fiber washout which leads to resin rich areas or nofills is not a function of fiber volume fraction but the strand integrity [103]. Gonzalez-Romero and Macosko [104] found that mat tearing depends on resin viscosity, fiber content and flowrate. Surface finish can also be a problem.

5.2.3 Process Limitations

Table 5.2 summarizes the processing limitations on geometry and microstructure for each alternative method. Manual production and automated cutting methods are able to produce the broadest range of part geometries with reasonable accuracy, high fiber volume fractions and low void content. Current automated prepreg layup methods have more restrictions on part geometry. Although fiber volume fraction, void content and accuracy of pultruded parts are comparable, the part geometry is very restricted. In comparison to prepreg methods, filament winding has lower fiber volume fractions, higher void content

Table 5.2 Limitations on Geometry and Microstructure

	hand layup and autocutting	tape layup and robotic transfer	pultrude	filament winding	RTM
V_F	62% [105]	62% [105]	60% [106,107,108]	60% [109] 49.4-57.5% [109]	47.4% [110]
V_V	<1% [111]	<1% [111]	<1% [108]	.5-5% [109] .5%', 3-8% [112]	-
fiber structure	2-D	2-D	1-D roving 2-D mat	2-D	3-D
inside radii	1/4" [113]	difficult	1/32" roving [114] 1/16" mat [114]	1/8" [115]	1/4" [113]
minimum thickness	.060" [113]	.060"†	.040" roving [114] .060" mat [114]	.010" [115]	.080" [113] .100" [116]
maximum thickness	no limit [113]	no limit†	3.0" roving [114] 1.0" mat [114]	2.0" [115]	.5" [113]
tolerance	±.005" [113]	±.005"†	±.005" [114,117]	±.010" [115]	±.010" [113]
corrugation	yes [113]	yes	yes [114]	concave only	yes [113]
molded holes	large [113]	large‡, no*	no [114]	no	no [113]
contours	yes	<±30° [118]	longitudinal	concave only	yes
hat section	yes [113]	yes†	yes [114]	no	yes [113]
cylinders	yes	difficult	yes	yes	yes
bosses	yes [113]	yes†	no [114]	no	difficult [113]
ribs	no [113]	no†	longitudinal [114]	no	difficult [113]
hollow section	no	no	longitudinal [114]	longitudinal	no

† based on hand layup data
* tape layup only
‡ robotic transfer only
' wound prepreg cured in autoclave

and more restricted part geometries. Fiber volume fraction is lowest for RTM but more complex geometries and 3-D fiber structures are possible.

5.2.4 Quality Relationships

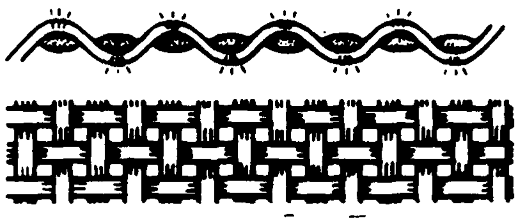
The microscopic process outputs are related to the substitute quality characteristics, such as material properties, part dimensions and surface finish. An example of a quality relationship would be the relationships between process outputs such as fiber structure, void content and resin/fiber system and the substitute quality characteristic material strength. In this section, the relationship between these process outputs and substitute quality characteristics will be examined.

5.2.4.1 Fiber Structure

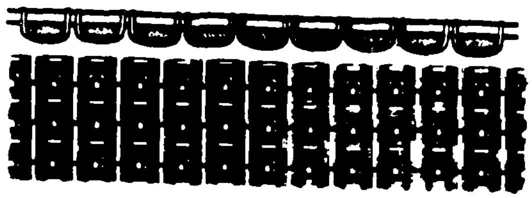
The type of fiber structure used for each alternative method varies in fiber orientation, fiber volume fraction and tow size. Unidirectional fiber tows, prepreg and multidirectional woven and knitted nonwoven fabric are the most common fiber forms used in advanced thermoset composites. Prepreg material forms and unidirectional pultrusion with fiber rovings tend to maximize fiber volume content. In pultrusion, the orientation is unidirectional throughout the part whereas in prepreg methods the orientation for each ply can vary. Resin transfer molding and multidirectional pultrusion require either 2-D or 3-D fiber forms resulting in lower attainable fiber volume fractions. The maximum attainable fiber volume fraction with adequate wetout is dependent on the fiber structure and the tow size.

The effect of weave distortion in multidirectional fiber forms can have a significant effect on the physical properties of composite structures. There are two basic types of 2-D fabrics, woven and knitted unwoven. In woven fabrics, the fibers follow an S-shaped path, sometimes referred to as crimp or weave distortion, as the fibers in one direction are passed over and under the fibers in the other direction. The stress caused by the crimp can reduce strength of the fiber form. Knitted unwoven fabrics, on the other hand, consist of reinforced fibers inserted into a knitted matrix usually made of polyester. The reinforcing fibers are laid flat eliminating the "crimp" problem. Unidirectional, biaxial and triaxial configurations are possible. Woven and unidirectional and biaxial knitted unwoven fabrics are shown schematically in Figure 5.2.

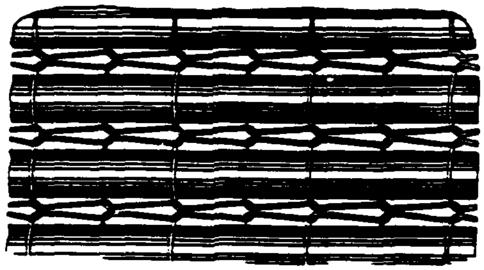
According to a recent article [119], knitted unwoven fabric is 30-65% stronger than woven fabric and its tensile delamination strength is as much as 200% higher. Four reasons are given for the superior strength characteristics of the knitted unwoven fabrics. First, the crimp-free fibers provide superior load translation since they are laid flat. Second, as the fibers straighten during loading, they do not pull away from the resin as much. Third, as the crimps are tightened in woven fabric, the plastic between warp and weft is sheared. Fourth, the warp and weft fibers can abrade each other at the crimps. Fabricators claim other advantages to knitted unwoven fabrics. These include higher volume fractions since less resin is necessary to wet out the fiber, increased wetout speed, because the knitted fabric channels resin more easily than the woven in which the crimps interrupt the flow, the elimination of fabric tearing and fraying and lower stress concentrations.



Woven Roving



Biaxial Knitted Unwoven



Unidirectional Knitted Unwoven

Figure 5.2 Comparison of Fiber Types [120, 121]

Advocates of 3-D fiber forms claim that for both 2-D and 3-D parts the more common failure mode is delamination. Therefore, although adding fibers transverse to the plane may decrease in-plane stiffness and strength by as much as 7% [122], many articles claim that it eliminates delamination as a failure mode since there are no planes for delamination. A recent paper [123], however, compared unwoven fabric with fibers added in the transverse direction to conventional tape laminates and found that the onset of delamination was about the same. Several researches believe that delamination is related to resin rich layers and not fiber form.

The size of the tow also has an effect on the quality of the end product. A recent article [124] describes the effect of fiber tow size on mechanical properties of braided fiber forms. Variations in fiber tow size caused variations in tensile, flexural and short-beam shear properties. As can be seen from the data in Figure 5.3, the 12K tow size specimens exhibited the best performance. The authors suggest that this may be created by the "crowding" effect of the braid yarns at the specimen edges which is more pronounced in 12K tow fibers. The 12K tow braided fibers also exhibited superior flexural properties. It appeared from photomicrographs that the larger tow sizes are more capable of inhibiting debond growth which was the apparent cause of flexural failure. For short beam shear 6K appeared to be the optimal tow size.

Since composites are not homogeneous materials, it is necessary to define material properties in all directions. The properties are usually determined in terms of an equivalent homogeneous material whose material properties are the same as the gross or macromechanical properties of a representative sample of the composite material. Many alternative methods have been developed to define the effective properties of composites ranging from an exact solid mechanics boundary solution to more approximate solutions in which either the geometry and/or the solution are approximated. Approximate geometries appear to be the most useful approach since even if the actual geometry can be quantitatively described, the actual geometry will vary from fiber bundle to fiber bundle.

The mechanics of materials approach, which is discussed in detail in [125], is used to develop simple approximations to the stiffness of 2-D unidirectional composite laminates. In this approach, it is assumed that the strains in the fiber direction of a unidirectional laminate are the same in both the fibers and the matrix. This is similar to assumptions in classical mechanics of materials approaches such as beam, plate and shell theories. The prediction of strength is more difficult since there are many possible failure modes.

For 2-D laminates made of unidirectional prepreg layers, the elasticity modulus in the fiber or 1 direction can be easily estimated by the mechanics of materials approach. Assuming that the average stress in the both the fibers and matrix acts on the cross-sectional area of the fibers and matrix, respectively, the elasticity modulus is given by the "law of mixtures"

$$E_1 = E_F V_F + E_M V_M \qquad (5.1)$$

where E_F and V_F is the fiber modulus and fiber volume fraction, respectively, and E_M and V_M is the matrix modulus and matrix volume fraction, respectively.

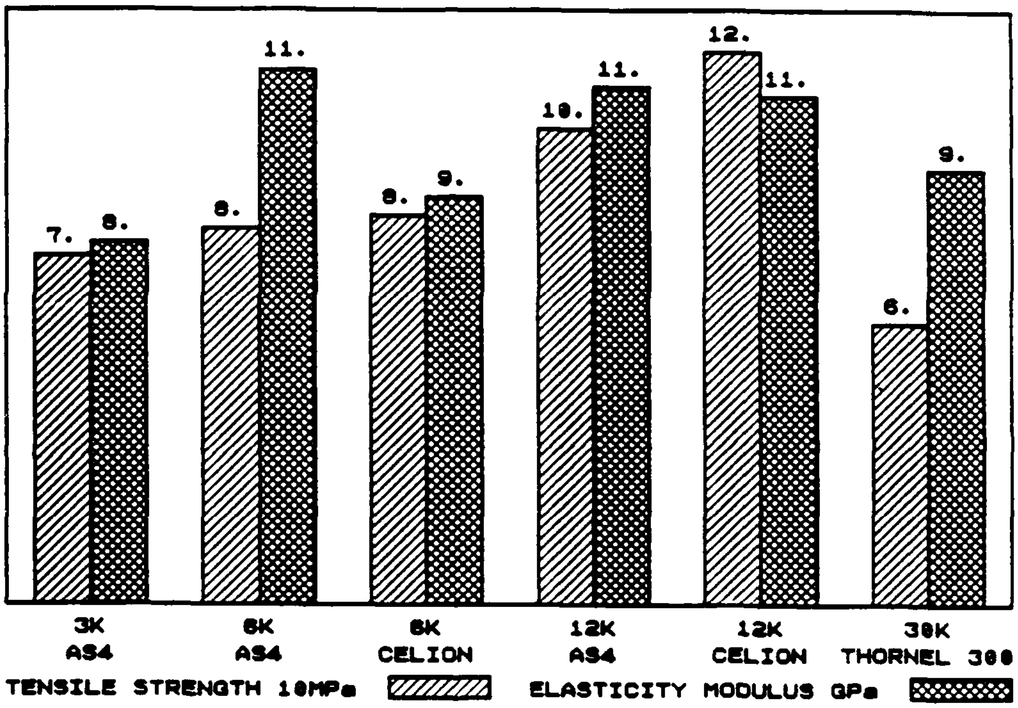


Figure 5.3 Effect of Tow Size on Material Properties

To determine the modulus in the matrix or 2 direction, it is assumed that the same transverse stress is applied to both the fiber and the matrix. The modulus in the direction transverse to the fibers is given by

$$E_2 = E_F\, E_M / (V_M E_F + V_F E_M) \tag{5.2}$$

These relationships are only estimates but are sufficient for comparison with the multidirectional fiber models.

Unidirectional fiber forms maximize the strength of the composite along the fiber direction. The variations in the angle of orientation may be caused by misalignment during the manufacturing process or may be necessary to increase strength in other directions or in the case of 3-D fiber forms prevent fiber movement. As the angle of orientation varies, there is, however, a dramatic decrease in the strength and stiffness of the resulting composite. Figure 5.4 shows the effect of orientation on the stiffness of the composite in the x and y directions for a graphite/epoxy laminate using the law of mixtures models. Since a 5% change in orientation can result in a 17% decrease in stiffness, process reliability becomes a very important issue.

For woven 2-D fabrics, two models have been developed by Chou et al. In their mosaic model [126, 127], the fabric is idealized as an assemblage of pieces of asymmetric cross-ply laminates. The fiber undulation model [128] takes into account fiber continuity and undulation and has been adopted for modeling the knee behavior of plain weave fabric composites. It appears that the stiffness of 2-D woven material can be approximated by the mechanics of materials models. Ishikawa and Chou [129] found that fiber undulation leads only to a slight softening of the in-plane stiffness and does not affect the stretching and bending coupling constants and confirmed this with two-dimensional finite element analysis. Results from another study on 2-D composite properties showed that the difference between 2-D woven and cross ply composites was less than 2% [130].

For multidimensional woven or knitted composites, the literature is more limited. In recent years, however, there has been substantial research interest in this area and several models summarized in [131] and ranging in complexity have been developed. Most of these models break up the composite into unit cells composed of fibers oriented in several possible orientations. The basic approach is to find the properties of each basic cell and then "average" these properties to determine macroscopic details. Chou has developed two models for analysis of 3-D fiber forms including the fiber interlock model which is based on minimization of strain energies [132] and the fiber inclination model which is based on classical laminated plate theory [133]. Many of these models including those described in [134, 135] use finite element techniques to determine the material properties.

An alternative to finite element techniques are more qualitative relationships. Ko [136, 137] uses law of mixtures and average orientation to determine strength and stiffness relationships. For the 2-D case, Piggott [138] assumes that the laminate is made up of an infinite number of microlaminae with fibers in different directions. By integrating the appropriate stiffness as a function of orientation angle, the in-plane modulus is given by

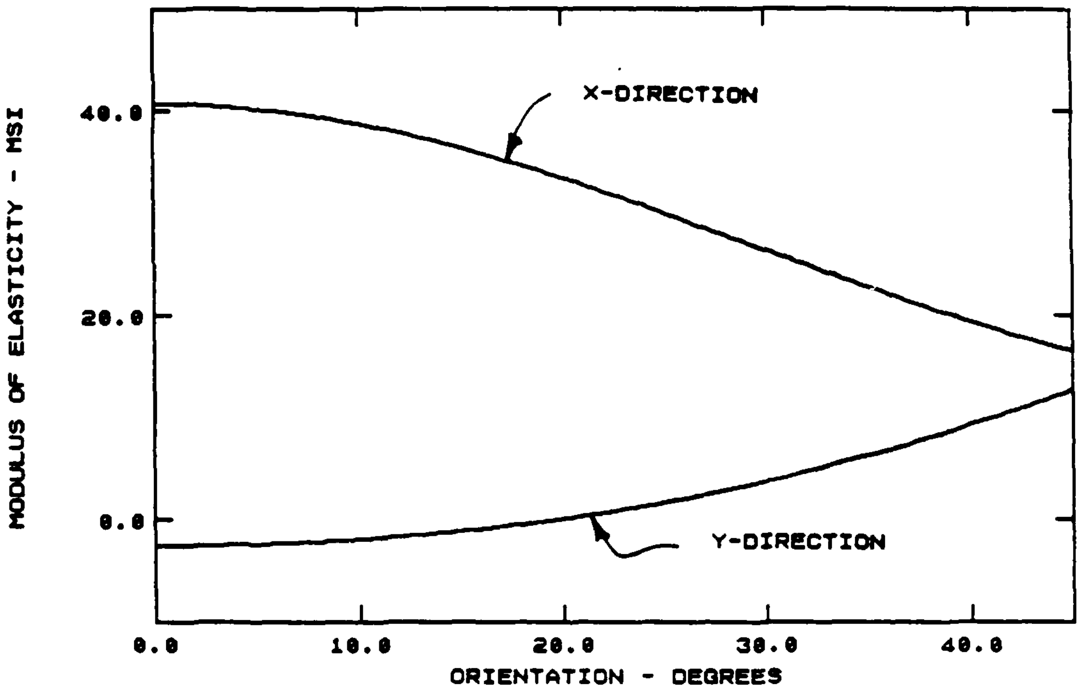


Figure 5.4 Effect of Fiber Orientation on Stiffness

$$E_R = 3/8\,(E_F V_F + E_M V_M) + 5/8\,(E_F E_M/(V_M E_F + V_F E_M)) \quad (5.3)$$

For the 3-D case of fibers oriented in random directions, the expression for modulus becomes

$$E_R = 1/5\ V_F\ E_F + V_M\ E_M \quad (5.4)$$

Despite their simplicity these approaches provide reasonable estimates of stiffness parameters when compared to actual data [139] and finite element solutions [140].

5.2.4.2 Void Content

The fact that voids degrade mechanical properties, especially those matrix dominated properties such as interlaminar shear strength, is well documented in the literature. The void content of a part will be dependent on processing parameters and, in some cases, on the fiber structure. Most of the void evidence in the literature is for consolidation of laminates. According to Kardos [141], voids can be formed either by entrapment of air or by nucleation. Air entrapment can be the result of resin mixing process, foreign particles such as tows, fuzz balls or broken fibers in the laminate, bridging between these particles, air pockets or wrinkles during prepreg layup and ply terminations. Nucleation can occur within the resin or at the resin/fiber or resin/particle interface. After cure, Kardos claims that most of the voids are found at the prepreg interface [142].

Documented evidence of void contents greater than 1% after autoclave processing are rare. In a study by Wenz and Mijovic [143] on the effect of temperature ramps in autoclave cycles on several properties, the average, minimum and maximum void contents were .184%, .030% and .433%, respectively. They found that the average void content for unidirectional laminates was 50% higher than that of the quasiisotropic laminates and that unidirectional laminates possessed a lower resin content. The authors thought the difference in resin content was because unidirectional plies appear to be more conducive to resin flow and compaction than the quasiisotropic plies. Postcuring the laminates resulted in a 50% decrease in void content. There was no correlation between heat up rate and void content. Although Hancox [144,145] claims that void content can be as high as 3%, acetone was used to create void contents greater than 1% in these studies.

In a recent study at McDonnell Aircraft Company [146], the effect of temperature and relative humidity on void content of laminates with 32 and 48 ply sections was studied. They observed that there existed a relatively defect free edge on many of the laminates which contained porosity and that most of the porosity was located in the thick or ply-drop off regions. Like Wenz and Mijovic, they found that unidirectional plies contained more porosity. The authors hypothesized that unidirectional laminates were more prone to porosity than crossplied laminates due to increased bleeding which reduced the permeability of the fiber network to the point where it restricted resin transport. High initial moisture content and high initial pressure which increased resin flow resulted in higher void contents. Laminates with low initial moisture had low void content regardless of compaction technique. Hot debulking every five plies reduced porosity of laminates with high initial moisture content.

The void evidence for processes which do not use prepreg are more scarce. Bascom [147] found both thin sausage shaped interfiber voids and larger crossfiber voids in glass filament wound cylinders in 1965. During the winding operation, air bubbles form in the resin bath and the resin cannot completely wet the fiber surface leading to void formation. In a recent article on filament winding, Elegante [148] noted many possible void sites between fibers, at roving crossovers and between layers of materials with different fiber orientations. Void contents range from 3 to 8% for wet winding and can be reduced by 1 to 2% by controlling resin application and by compacting the component during winding. Use of prepreg materials with pressure, vacuum and autoclave cure can reduce void content to .5%. In another filament winding study [149], 8.4 inch diameter graphite/epoxy cylinders were fabricated varying in fiber orientation and type of resin with void contents between .5 and 5.0% and fiber volume fractions between 49.4 and 57.5%. These cylinders compared favorably in material properties with autoclave cure panels.

A study of ultrasonic enhancement of the pultrusion process of epoxy materials by Tessier et al. [150] found no voids present in pultruded stock of either the ultrasonically activated or the nonactivated die. A recent study [151] showed that the type of resin impregnation method used in conjunction with multidirectional fiber forms can have a dramatic effect on the void content of the parts. Four impregnation procedures were investigated including vacuum impregnation, pressure impregnation, resin film lamination and a closed mold resin impregnation method. The latter method was more complicated but produced consistent fiber and resin volume fraction and a void content of less than 1%.

Judd and Wright [152] summarizes the results of several studies on the relationship between void content and mechanical properties. These studies show that interlaminar shear strength, longitudinal and transverse strength and modulus, compressive strength and modulus, fatigue resistance and high temperature resistance of composites decrease as void content increases regardless of type of resin, fiber or the fiber/resin interface. Experimental evidence indicates that interlaminar shear strength (ILSS) decreases 7% for a 1% decrease in void content and that the decrease in ILSS is nearly linear up to 4% void content. Other properties experienced decreases to a lesser degree. Since parts are rarely void free, Yoshida et al. [153] tried to determine allowable limits on void content for quality assurance purposes. They concluded that unidirectional carbon-epoxy with .45% void content and bidirectional carbon/polyester composites with .95% void content do not vary significantly from void free composites.

Hancox [154] studied the influence of voids on the hydrothermal response of carbon reinforced plastics. He found that specimens with higher void contents absorb more water at 40°C and the effect is magnified as the temperature of the water increases. With the exception of shear strength, the effects of moisture and temperature exposure are not reversed on drying out for specimens with void contents over 1%. A recent study on hygral and mechanical properties of AS4/3502 graphite/epoxy by Harper et al. [155] showed that matrix dominated moduli E_{22} and G_{12} were found to depend significantly on void content. The fiber dominated properties, E_{11} and ν_{12}, however, were not dependent on void content. The shear strength, G_{12}, decreased 50% for a 4% increase in voids. The elasticity moduli, E_{22}, decreased less than 20%. Panels with V_V of 5% absorbed water faster than panels with V_V of 1%.

Delamination is considered to be one of the predominant types of damage in composites. There are not, however, many studies on the effect of void content on delamination. In a survey paper by Johnson et al. [156], it is noted that delamination is enhanced especially when interply or interlaminar porosity occurs. Currently, Tsai [157] is investigating the effect of porosity on the delamination of resin-matrix composites. His preliminary studies have shown that laminates with artificially induced high porosity content exhibit higher mode I delamination fracture energies. He hypothesizes that an irregular crack plane and matrix multiple microcracking produce the higher fracture energies. There appears to be no significant effect of porosity on mode II delamination resistance.

5.2.4.3 Resin/Fiber Systems

Generally viscosities less than 2,000 cps and a reasonably long pot life are necessary for proper fiber wetout [158] for wet systems. Therefore, filament winding, pultrusion and resin transfer molding require different resin systems from those used in prepreg. Tables 5.3 and 5.4 give fiber and neat resin properties for Hercules AS4 graphite fibers and epoxy resin systems, respectively. EPON resin 9310 with curing agent 9360 and EPON resin 9400 with Curing Agent 9450 were developed by Shell for pultrusion and RTM and filament winding, respectively. Typically, the tensile moduli for epoxy resin used in prepreg range between 320 and 750 ksi [159]. The matrix dominated properties will be higher for prepreg methods.

Table 5.3 Graphite Fiber Properties [160]

tensile strength, ksi	550
tensile modulus, ksi	34,000
tensile strain, %	1.50
approximate yield, ft/lb	6,800

Table 5.4 EPON Resin Properties [161]

resin	9310	9400
curing agent	9360	9450
tensile strength, ksi	11	11
tensile moduli, ksi	453	450
tensile ultimate strain, %	4.0	4.5
flexural strength, ksi	-	19

5.2.5 Cost/Quality Tradeoffs

The true quality of a product can be related to substitute quality characteristics through quality analysis and statistics. These characteristics are measurable parameters which can be used to compare the relative quality of alternative methods. In Section 3, it was assumed that all parts were of similar quality and would therefore satisfy the customers requirements equally. There are, however, many process limitations which lead to inherent differences in material strength and geometries. In situations in which the part can be redesigned to meet the customer's needs, the cost comparison must be modified to reflect these changes.

Since quality is dependent on requirements of the user, an example is needed to illustrate the effect of true quality on manufacturing cost. For a given set of customer requirements, the substitute quality characteristics were specified in terms of maximum deflections for a given applied load and the ability to withstand a given interlaminar shear moment. The requirements were satisfied by the properties of a $(0°/90°)_{6S}$ laminate fabricated from prepreg materials. To produce parts which would also satisfy these constraints RTM and filament winding, the thickness of the part must be increased in order to compensate for lower fiber volume fractions, higher void contents and inferior resin properties. Pultrusion can not meet these specs without an order of magnitude increase in thickness.

Table 5.5 compares estimates for tensile moduli in x and y directions for average fiber volume and void content and the appropriate fiber structure. Since pultrusion produces only unidirectional parts, the elasticity modulus in the y direction does not meet customer's requirements. Similarly, the lower fiber volumes of filament winding and RTM result in lower properties. In addition, the ILSS strength of filament winding with oven cure is reduced by 35% due to the 5% void content. Increasing the thickness of laminate by 14%, 35% and 33% for filament winding with autoclave cure, filament winding with oven cure and RTM, respectively, will satisfy the specifications. Since the thickness of a pultruded part must be increased over ten times, it was not considered.

Table 5.5 Comparison of Part Properties

	prepreg methods	pultrusion	filament winding	RTM
V_F	62%	60%	55%	47%
V_V	<1%	<1%	<1%†, 5%*	-
structure	$(0°/90°)_{6S}$	$(0°)_{24T}$	$(0°/90°)_{6S}$	$(0°/90°)_{6S}$
E_1	21.3 msi	20.6 msi	18.9 msi	16.2 msi
E_2	1.28 msi	1.11 msi	.98 msi	.84 msi
E_X	11.3 msi	20.6 msi	9.9 msi	8.52 msi
E_Y	11.3 msi	1.11 msi	9.9 msi	8.52 msi

† autoclave cured * oven cured

Figure 5.5 compares the manufacturing costs for these parts for an annual production volume of 5,000 parts. Although the non-prepreg methods are more cost effective than prepreg methods, the relative cost savings is substantially less.

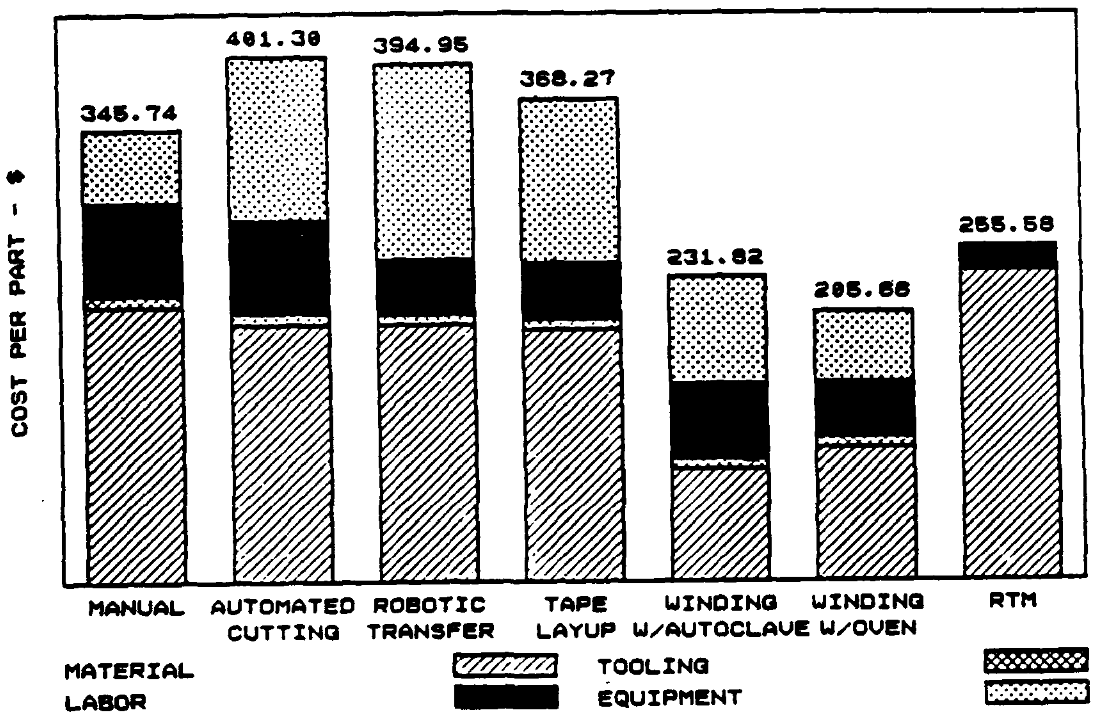


Figure 5.5 Breakdown of Part Cost

Filament winding with oven cure is the most cost effective process in this example due to its low equipment costs and ability to produce cross ply components. Although the equipment and labor for RTM are still low, the material costs are comparable to those of prepreg methods. Filament winding offers a cost competitive alternative without the substantial increase in weight necessary to meet the user's requirements for the other processes.

Frequently, a given method, despite potential redesigns, will not be able to consistently produce a part which will satisfy all of the user's requirements. A cost which reflects this loss in quality after the part was been shipped would include cost due to customer service and customer dissatisfaction. Service cost is incurred directly and can be included in accounting procedures. Customer dissatisfaction leads to loss of market share and profits and extra sales costs to recapture market share. To quantitatively describe these costs, Taguchi [162] has suggested a quadratic quality loss function given by

$$L = \frac{L_C}{\Delta_C^2} (Y - M)^2 \qquad (5.5)$$

where Y is the value of a performance parameter, M is the target value of the performance parameter, L_C is the customer loss and Δ_C is the customer tolerance. The customer tolerance is representative of the variation that the average customer will tolerant before seeking service and the customer loss is the cost of that action.

5.3 Quality Examples

The relative quality of alternative methods is difficult to quantify. This subsection will demonstrate the use of process models and the basic framework to quantify process quality and relate it to cost.

5.3.1 Human Error

The cost analysis indicates that the capital investment in alternative prepreg layup methods cannot be justified on labor savings alone. It is assumed that the manual and machine assisted prepreg layup methods have similar error rates. According to Ayres [163], as part complexity and required level of precision increases, the ability of human workers with an inherently large error rate to produce quality products is greatly impaired. Automated equipment is far more reliable than humans since they have an a priori probability of error per opportunity much lower than humans. Since costs for correcting poor quality can exceed 30% of the total process cost in the composites industry [164], more consistent quality may give the machine assisted methods an advantage.

Human error models, based on information theory, can help to quantify the error rate. Humans are inherently error-prone. Emotional stress, physical strain, interference, illumination and a high information load tend to increase their error rate. The human error rate generally exceeds 1 per 1000 opportunities [165]. Inspection and redundant design reduce this rate to a critical undetected error rate of 1 per 100,000 opportunities. Automation reduces this error rate by at least an order of magnitude. During the layup process, there are many opportunities for error including cutting accuracy, orientation, ply placement, extra or missing plies and errors in autoclave preparation process.

Since data was not available to determine the relative error rate for each process, it was assumed that automated methods have the same number of opportunities for error per task but that the error rate per opportunity is an order of magnitude less. It is assumed that the error rate for a method is a function of the amount of manual cycle time that is automated. The costs related to correcting poor quality for a partially automated process are given by

$$C_Q = C_{Q0}/t_m \left\{ e_m \sum_{i=1}^{N} t_{mi} + e_a \sum_{i=1}^{M} t_{ai} \right\} \tag{5.6}$$

where C_{Q0} is the nominal cost to correct poor quality of 30%, t_m is the total manual cycle time, t_{ai} is the cycle time of the ith automated step, t_{mi} is the cycle time of the ith manual step, e_m is the manual error rate, e_a is the automated error rate, N is the number of manual tasks and M is the number of automated tasks.

Based on cycle times for a 4 ft^2, 24 ply part, the cost for correcting quality are 30%, 25.7%, 8% and 8% for manual production, automated cutting, robotic transfer and tape layup, respectively. Figure 5.6 gives the cost for producing this part adjusted for quality related costs. Comparison to Figure 3.1 shows that the breakeven points for the prepreg methods are substantially lower. The breakeven points are 13,000, 2,800 and 4,1000 parts for automated cutting, robotic transfer and tape layup. If automated methods are able to decrease the error rate as they have in other industries, the cost savings are substantial.

5.3.2 Autoclave Laminate Consolidation

Voids have long been considered a major problem in the processing of composites. Process models for laminate consolidation and void stability can be used to define a processing window in which void content is minimal and quality is enhanced. A general mathematical model has been developed by Gutowski et al. [166] to describe the one dimensional consolidation of composite laminates with three dimensional resin flow. The model assumes that resin flow can be modeled using Darcy's law for flow through porous medium and that the fibers behave like a deformable nonlinear elastic network. During the consolidation process, the applied pressure is carried by both the resin and the fibers. Initially, the resin carries the load causing the resin to flow out of the laminate into bleeder plies. As the resin flows out, the laminate consolidates deforming the fiber bundles. Eventually the fiber bundles carry most or all the load resulting in very low or no resin pressure.

Using momentum, Darcy's law and resin and fiber continuity, an equation for resin pressure distribution in the resin as a function of fiber bed permeability, fiber volume fraction and viscosity can be derived. Since the applied pressure and dominant resin flow are transverse to the laminate, the

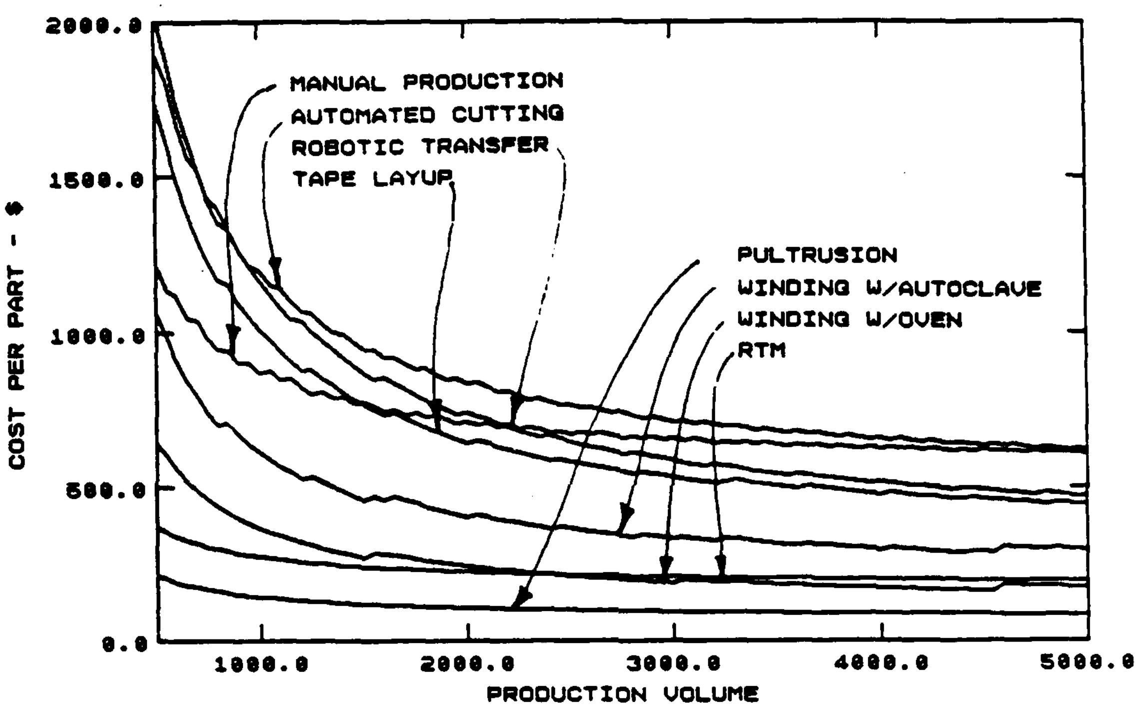


Figure 5.6 Part Cost Adjusted for Quality Related Costs

problem reduces to a one dimensional consolidation equation, shown schematically in Figure 5.7, given by

$$\frac{\partial V_F}{\partial t} = \frac{1}{\mu}\frac{V_F^2}{V_0^2}\left\{V_F S_{ZZ}\frac{\partial^2\sigma}{\partial z^2} + \frac{(V_F S_{ZZ})'}{\sigma'}\left(\frac{\partial\sigma}{\partial z}\right)^2\right\} \tag{5.7}$$

where σ is the stress in the fiber bundles, V_0 is the initial fiber volume fraction, S_{ZZ} is the fiber permeability in the z direction, and the prime indicates differentiation with respect to V_F. The boundary and initial conditions are: at $t = 0$, $V_F = V_0$, at $z = 0$, $\partial V_F/\partial z = 0$ and at $z = h_0$, $p = \sigma(V_F)$.

The stress in the fibers is given by the expression

$$\sigma = A_S \frac{((V_F/V_0)^{.5} - 1)}{((V_A/V_F)^{.5} - 1)^4} \tag{5.8}$$

where A_S is a material constant and V_A is the maximum available fiber volume fraction. The permeability of the fiber bed is given by

$$S_{ZZ} = \frac{r_F^2\,(1 - V_F)^3}{4\,k_{ZZ}\quad V_F^2} \tag{5.9}$$

where k_{ZZ} is the Kozeny constant. Empirical expressions for viscosity and degree of cure were developed by Loos [167]. The viscosity in Pa sec is given by

$$\mu = 7.93\text{x}10^{-14}e^{(U/RT + 14.1\alpha)} \qquad \text{if } \alpha < .5 \tag{5.10}$$

$$\mu = 7.93\text{x}10^{-14}e^{(U/RT + 14.1\alpha)} + 10(1 - e^{-5(\alpha - .5)}) \qquad \text{if } \alpha > .5 \tag{5.11}$$

where R is the gas constant, U is the activation energy of the resin of 90,800 J/mole, T is the temperature in degrees Kelvin and α is the degree of cure. The incremental degree of cure is given by

$$\Delta\alpha = (3.5\text{x}10^7e^{-80,700/RT} - 3.36\text{x}10^7e^{-77,800/RT}\,\alpha)(1 - \alpha)(.47 - \alpha) \qquad \text{if } \alpha < .3 \tag{5.12}$$

$$\Delta\alpha = 3,266e^{-56,600/RT}(1 - \alpha) \qquad \text{if } \alpha > .3 \tag{5.13}$$

This model for resin pressure can be combined with the void model developed by Kardos et al. [168]. The first phase of the model predicts void formation and equilibrium stability. It estimates an upper bound on conditions necessary to produce a void. The second phase predicts void growth or dissolution by diffusion. The third phase deals with the removal of voids by resin flow. The basis of the Kardos model is that water is the main void agent, although air voids can present a site for air/water vapor void nucleation. He sites two references which verify this assumption. Grayson and Wolf [169, 170] used precision abrasion mass spectrometry to determine that water was the main

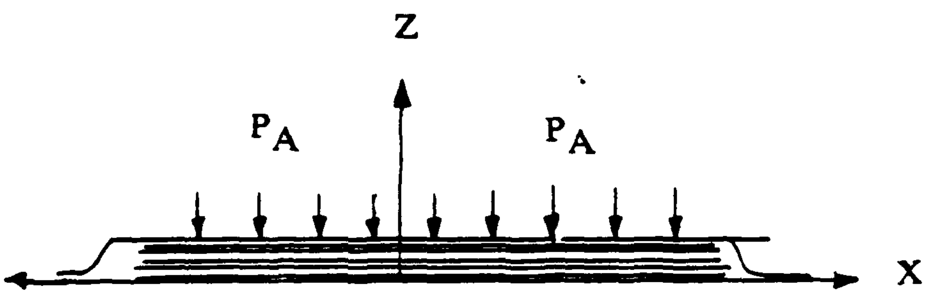


Figure 5.7 Schematic of the Consolidation Process

component in voids. Work done at General Dynamics [171] showed that water-stabilized air or water alone and not trapped air alone was the source of the void problem.

Kardos uses classical nucleation theory [172] to derive a rate equation for nucleation of air or water voids. It is assumed that pure air voids will collapse since the pressure in them is not sufficient to prevent their collapse during pressurization and compaction. If water vapor diffuses into an air void, however, the void pressure can exceed the surrounding hydrostatic resin pressure and surface tension forces. Raolt's law is used to model the pressure in the void as an ideal gas and determine an upper bound. Using this relationship, void growth will not occur if the water concentration gradient opposes water diffusion into the void.

To prevent pure water void growth by diffusion at all times and temperatures during the cure, the minimum pressure at all points in the prepreg must satisfy the inequality

$$P_R \geq 4962\, e^{(-4892/T)}\, (RH)_0 \tag{5.14}$$

where P_R is the resin pressure, T is the temperature during the cure cycle and $(RH)_0$ is the relative humidity exposure of the prepreg. Experimental evidence to verify the validity of this void model is limited. In a recent article [173], the model was used to successfully predict whether or not voids would form for a selected autoclave cycle at relative humidity exposures of 35% and 85%. The resin pressure void suppression inequality above successfully predicted that only the prepreg exposed to the highest humidity would produce voids. Experiments by Yokota [174] may also provide evidence to support this model.

The consolidation process was simulated to determine if the void suppression inequality was satisfied for several different laminate thicknesses for the temperature profile shown in Figure 5.8. Figure 5.9 shows the minimum resin pressure for this temperature profile which satisfies the void suppression criteria as the cure cycle progresses. Pressure was applied 70 minutes into the cure cycle. Figure 5.10 plots the magnitude of the applied pressure versus the fiber volume fraction for several part thicknesses. The wavy lines indicate the acceptable moisture level for producing void free parts under these conditions. The graph indicates that the resin pressure in thicker laminates is sufficient to suppress the formation of voids. Thin parts, however, have very high fiber volume fractions but are more susceptible to void formation. In these parts, most of the resin has been bled from the laminate. Since the fiber bundles are carrying most of the applied pressure, the pressure in the resin is very low and insufficient to suppress voids.

A high quality manufacturing process will process consistent quality despite variations in processing parameters. The consolidation model discussed in the previous subsection was also used to evaluate the sensitivity of the consolidation process to temperature and pressure variations. To simulate variations in pressure and temperature, white noise was fed through a discrete first order filter with a 1800 second time constant. Figures 5.11 and 5.12 show typical pressure and temperature profiles.

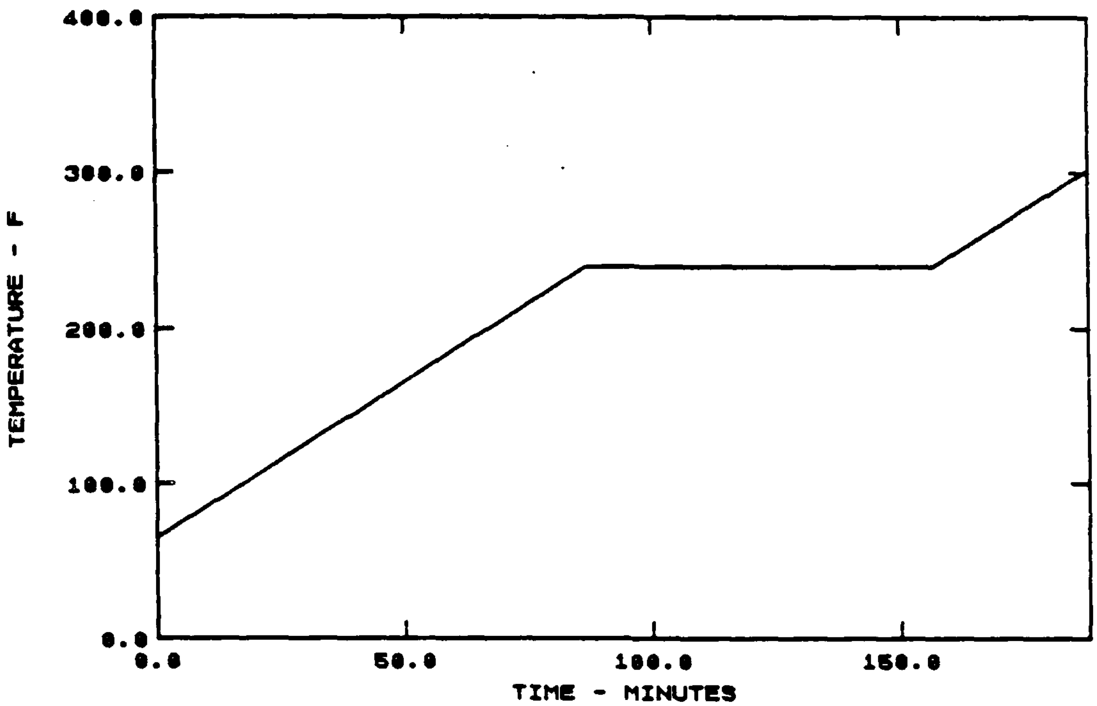


Figure 5.8 Cure Cycle Temperature Profile

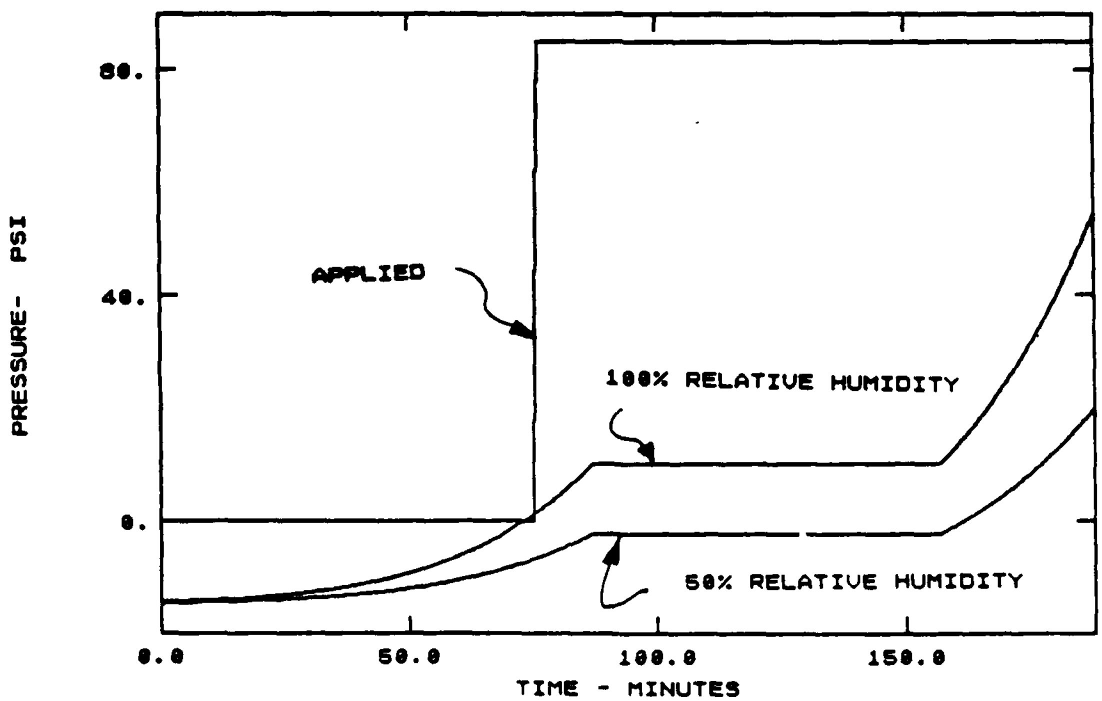


Figure 5.9 Applied and Void Suppression Pressures

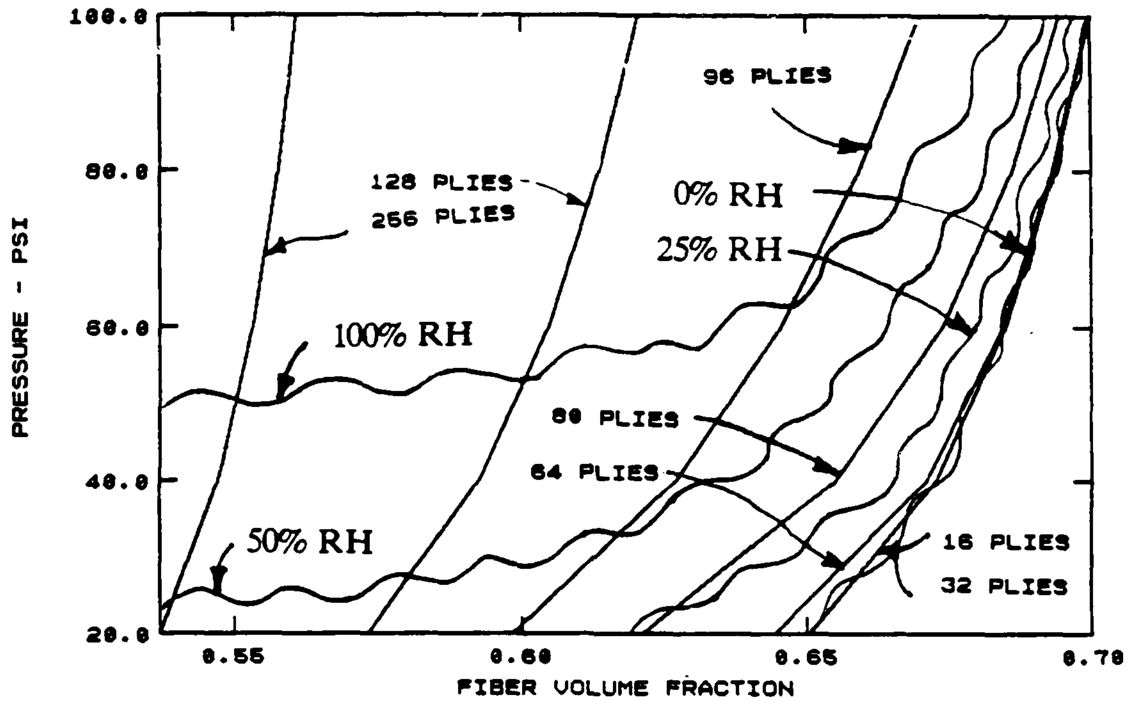


Figure 5.10 Effect of Relative Humidity on Fiber Volume Fraction

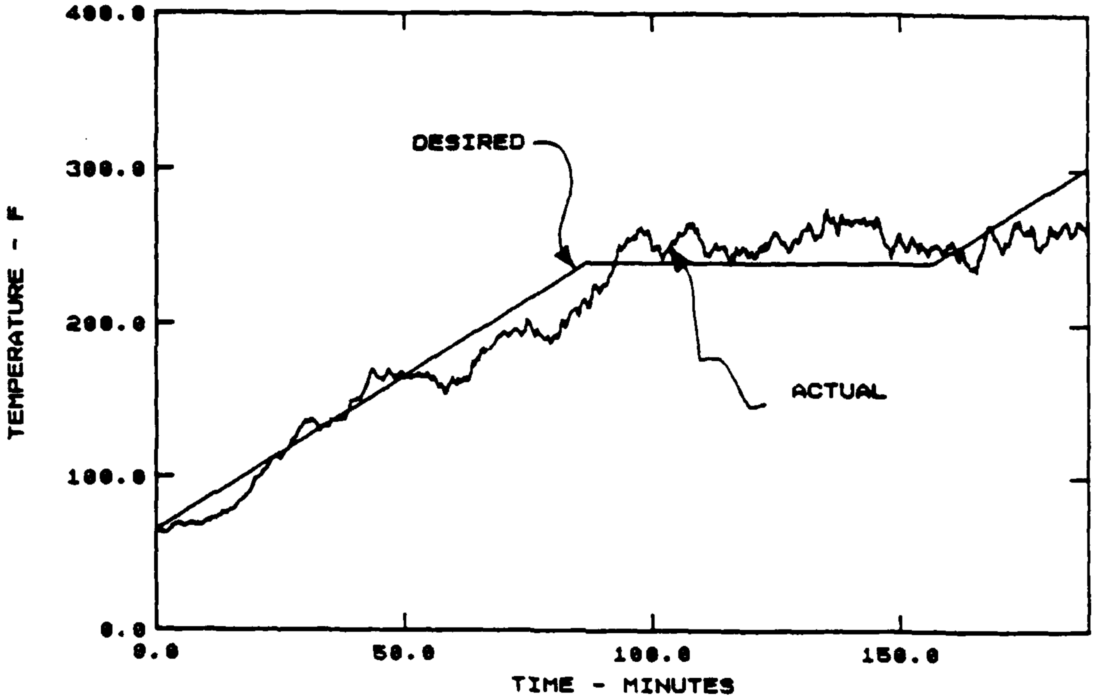


Figure 5.11 Fluctuations in Temperature Profile

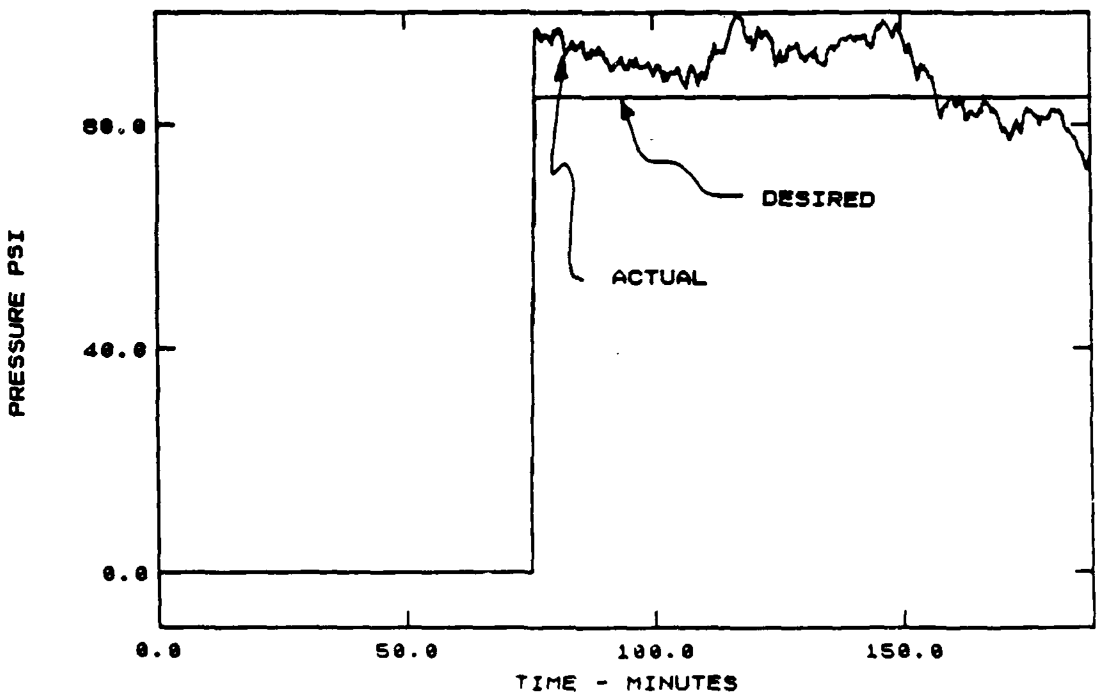


Figure 5.12 Fluctuations on Pressure Profile

Figure 5.13 shows the standard deviation of fiber volume fraction normalized by its magnitude as laminate thickness increases. The thickness variations are low indicating that the autoclave process is not very sensitive to cyclic variations in temperature and pressure. As the laminate thickness increases, variations in normalized fiber volume fraction decrease both for fluctuations in temperature and pressure. Temperature affects the viscosity and the degree of cure and the point at which flow ceases. For thin laminates, since most of the resin is bled from the laminate before the resin gels, the fiber volume fraction is sensitive to pressure and temperature effects. For thicker laminates, the resistance to flow is greater and fiber volume fraction is less sensitive to pressure and temperature variations.

5.3.3 RTM Process Limitations

In RTM, there is an inherent tradeoff between moldability and fiber volume fraction. The volume of fibers and the ultimate strength is limited by the permeability of the fiber form and the viscosity and geltime of the resin. A simple model based on the flow through porous media demonstrates this tradeoff in parameters. In Section 2.3.2.1, the cycle time was calculated as

$$t_{MF} = \frac{\mu\, l_{rp}^2}{2\, S\, \Delta P} (1 - V_F) \tag{5.15}$$

The permeability can be related to the fiber volume fraction by the Carman Kozeny equation

$$S = \frac{r_f^2\, (1 - V_F)^3}{4\, K\, V_F^2} \tag{5.16}$$

where K is the experimentally determined Carman Kozeny constant. Substitution gives

$$t_{MF} = \frac{8\, \mu\, K\, l_{rp}^2 \quad V_F^2}{r_f^2\, \Delta P \quad (1 - V_F)^2} \tag{5.17}$$

To prevent nofills, which are caused by premature gelling of the resin, the general rule of thumb is to fill the mold within 25 to 50% of the geltime [175]. This requirement can be expressed in terms of the permeability as

$$S_{MIN} = \frac{\mu\, l_{rp}^2}{2\, \Delta P\, \alpha\, t_g} (1 - V_F) \tag{5.18}$$

where S_{MIN} is the minimum permeability for a successful part, α is the ratio of geltime to fill time of .5 and t_g is the geltime. The size of the part, therefore, will be restricted by the fiber form permeability which is related to the fiber volume

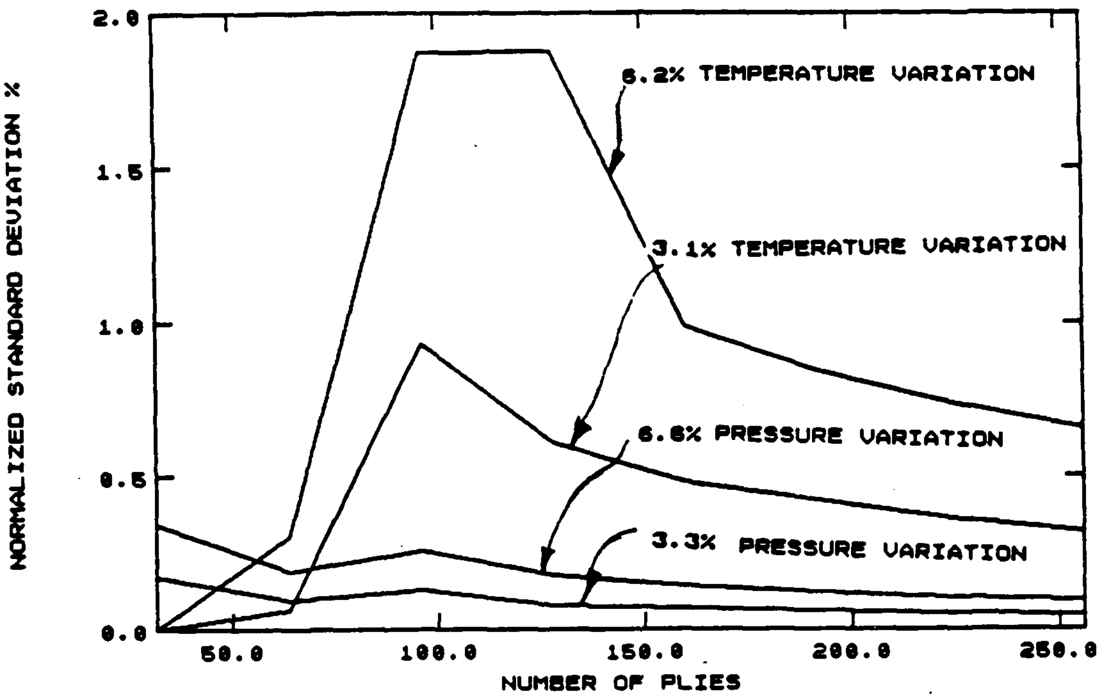


Figure 5.13 Variation in Normalized Fiber Volume Fraction

fraction. As the viscosity to geltime ratio decreases, the maximum attainable fiber volume is increased due to a decrease in minimum permeability.

Figure 5.14 summarizes the results of permeability studies for several fiber forms. The permeability data for woven graphite mat by Rogowski [176] and Owen Corning glass mat, OCM8605, by Martin and Son [177] has been fit to the Carman Kozeny equation with values of K of 2.58 and .35, respectively. Although additional data for OCM8605 by Gauvin et al. [178] exhibits a fair amount of scatter, it also roughly correlates with the Carman Kozeny equation. Data for Hexcel glass mat and fiber braidings by Woven Structure are based on work by Coulter et al. [179] and unpublished experimental results at the Princeton Textile Research Center [180]. Although three dimensional fiber forms have a higher permeability for a given fiber volume fraction, the maximum attainable fiber volume fraction is lower than that of two dimensional fibers resulting in inferior strength and stiffness properties. Adams et al. [181] noted that permeability is sensitive to structural variations involving weave type, sett balance, yarn shape, fiber orientation and compressibility.

Since the fiber bed is dry before the resin reaches it, the permeability should be modified to account for the wetting force as the liquid first advances through a dry fiber bed. This was done by Williams [182] who showed that the direct theoretical effect of wetting is very small. Experimentally, however, dry beds appear to have a higher value of permeability. Williams postulated that surface tension modifies air entrapment and thereby the flow rate and distribution of fibers resulting in a higher permeability. Carman [183] found that permeability can vary with porosity if there is any irregularity of packing. Williams [184] and Martin [185] have reported that a dry bed increases the permeability by a factor of 2 and 16, respectively.

Data for EPON Resin 9400, an epoxy resin produced by Shell Chemical Company for RTM and filament winding, is given in Table 5.6. According to Vaccarella [186], resins with viscosities between 200 and 300 cp produce the best results. Above this range, the high pressures washout the reinforcement. Below this range, there is a tendency to entrap air.

Table 5.6 EPON Resin 9400 Specifications [187]

Temperature °C	Viscosity cp	Geltime min
82	50	110
121	10	26
149	6	7.5

Figure 5.15 shows cycle time versus fiber volume fraction for different values of the Carman Kozeny constant for an inlet pressure of 25 lb/in^2, volumetric flow rate of 396 in^3/min, geltime to filltime ratio of 50% and a resin path length of six inches. For K = 1 and 5, the part cannot be produced after the cycle time increases beyond 13 minutes at a fiber volume fraction of .40 and .60, respectively. For comparison, woven graphite mat has a Carman Kozeny constant of 2.58. The limitations on fiber volume fraction are primarily a design

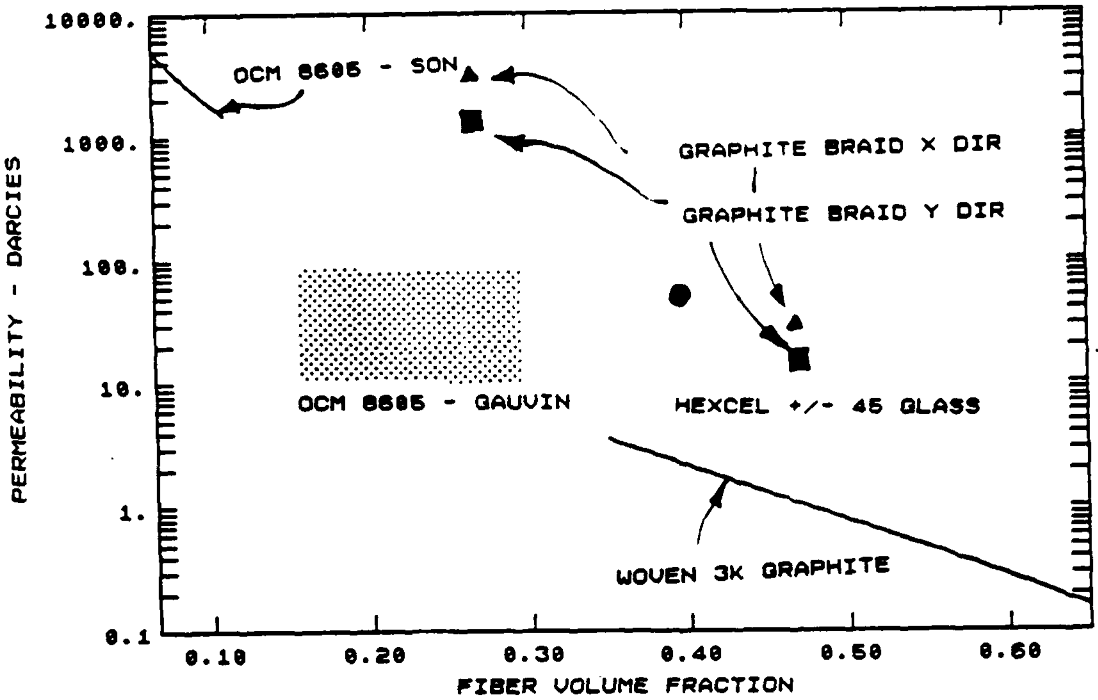


Figure 5.14 Permeability Data for Several Fiber Forms

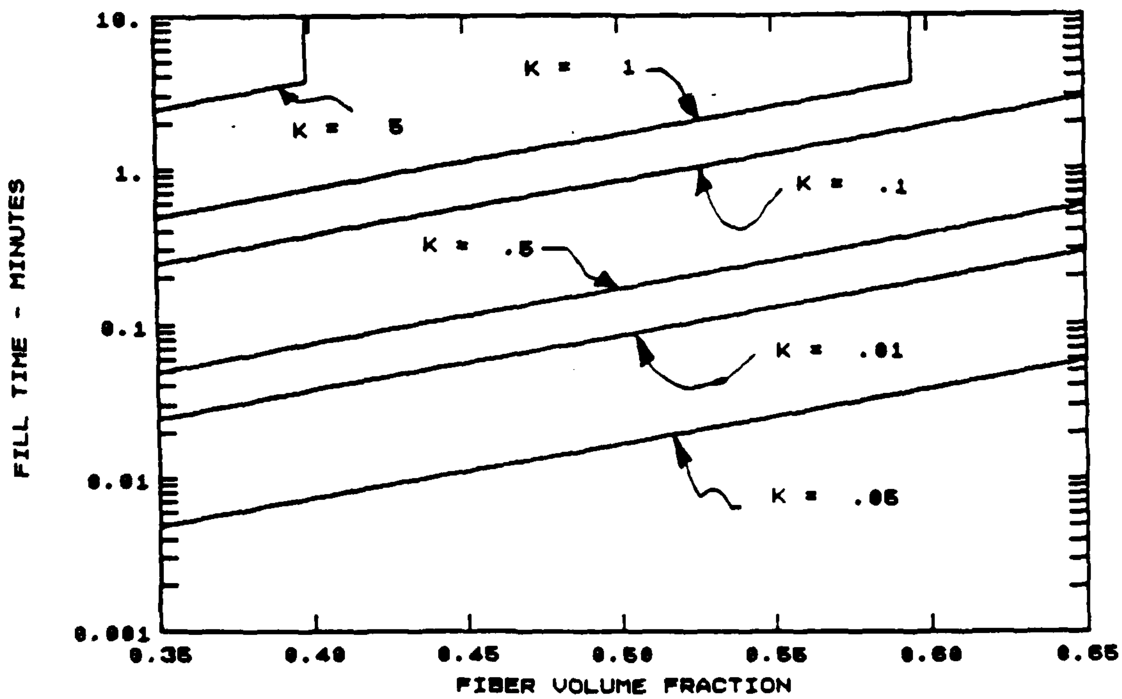


Figure 5.15 Cycle Time Versus Fiber Volume Fraction

and cost issue. Lower fiber volume fractions correspond to a compromise in part properties. Additional strength and stiffness can, however, be achieved by increasing the thickness of the part. This will mean added weight and increased part cost due to additional material and increased cycle times which the design may not tolerant

Figure 5.16 shows cycle times versus desired fiber volume fraction for .250 inch thick parts produced with woven graphite mat of varying length. The fiber volume fraction will be limited by the resin viscosity, geltime and the resin path length. For EPON 9400 resin, the cycle time is minimum when the ratio of viscosity to geltime is at a maximum at 149°C. At this temperature, however, it is not possible to produce parts which require more than 3.75 minutes to fill. Decreasing the process temperature to 121°C lowers the viscosity to geltime ratio and enables one to produce parts with cycle times up to 13 minutes. After the cycle time reaches 13 minutes, the desired fiber volume fraction can no longer be met. Instead the part thickness is increased enough to increase the volume of fibers to correspond to the volume of fibers in a part of the desired fiber volume fraction and the original part thickness.

The economic model was used to compare the cost of producing flat laminates by hand layup, tape layup and resin transfer molding. Figure 5.17 shows the increase in manufacturing cost for a 6 in by 48 in by .250 inch part with a desired fiber volume fraction of .65 for an annual production volume of 5,000 parts as the desired fiber volume fraction increases. Woven graphite mat, with a maximum attainable fiber volume fraction for this size part of .45, was the reinforcing material used in the RTM process. To compensate for the lower fiber volume fraction, the thickness of the part was increased to produce a part with the same volume of fibers but more weight.

Since the fiber volume fraction for prepreg remains constant, manual layup and tape layup are represented by a point. To illustrate the effect of the large variation in fiber form cost, the production costs for the least and most expensive fiber forms are plotted. As the desired fiber volume fraction increases, the cycle time increases causing an increase in equipment utilization. This effect, however, is dominated by the increase in fiber costs due to the increase in fiber volume. Although the thickness of the part must be increased after a fiber volume fraction of .45, this does not have a noticeable effect on the part cost, since the additional resin cost is small in comparison to the cost of the fibers. As indicated in the figure, the manufacturing cost for manual production and tape layup are higher even for the most expensive fiber form.

5.4 Conclusions

Quality is an important issue facing the composites industry today. Since true quality is related to the ability of a product to satisfy the customer's requirements, it is difficult to quantify. Quality can be defined in terms of process limitations and process variability. The raw material methods are subject to many geometric limitations and in some designs may compromise the superior material properties of prepreg methods. Human error can lead to a large increase in quality related costs. If automated prepreg methods can eliminate or reduce these quality related costs, their ability to compete economically with manual production is enhanced.

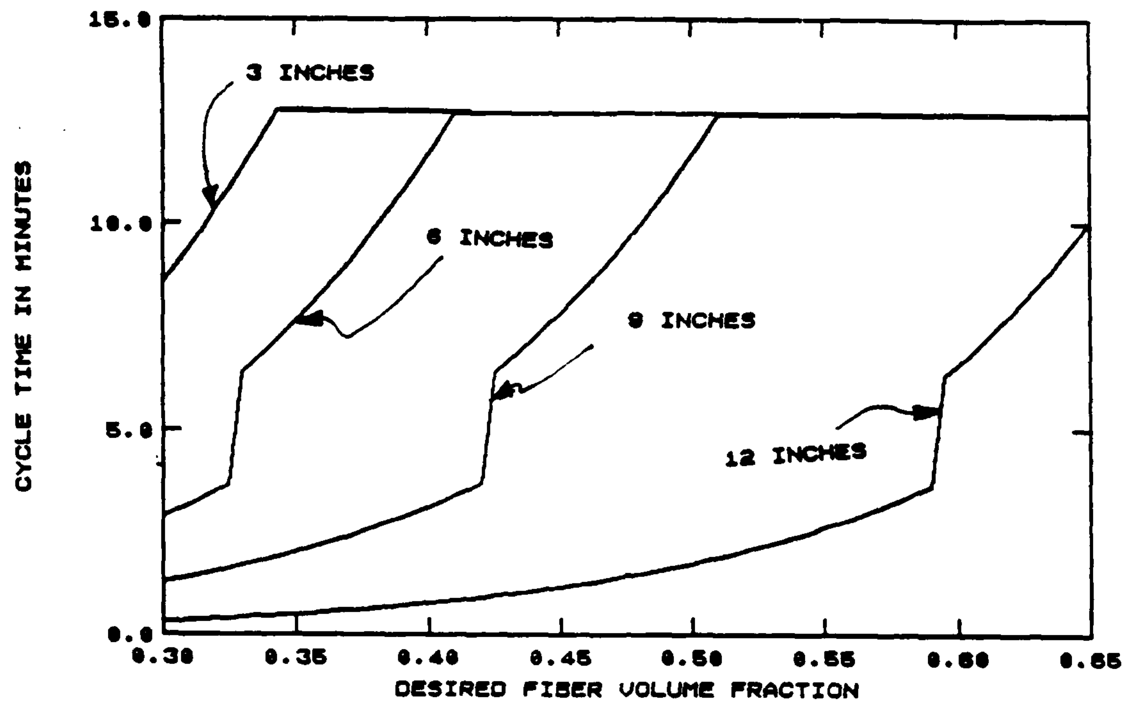


Figure 5.16 Cycle Time Versus Desired Fiber Volume Fraction

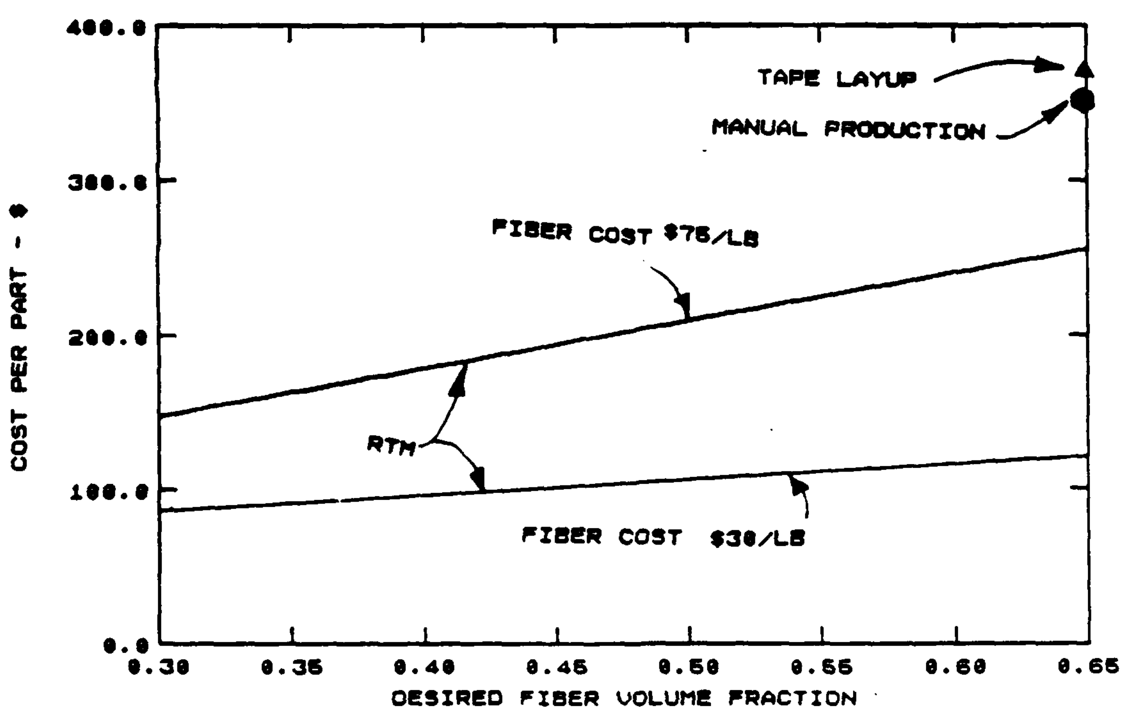


Figure 5.17 Part Cost Versus Desired Fiber Volume Fraction

6. Conclusions

Since current methods for fabricating composite structures are time consuming and subject to the skill of the worker, several alternative manufacturing technologies have been proposed to replace or assist manual production. Quantitative measures have been developed to compare the economic benefits, quality and flexibility of alternative manufacturing technologies. An economic model was developed to compare direct labor and material savings to the capital investment in automation equipment. Quality was assessed in terms of process limitations and variability. Simulation techniques were used to evaluate the tradeoff between response time and manufacturing cost. This basic technique could be applied to evaluate alternative methods in other industries.

The results of the economic analysis stress the strong influence of material costs on the cost effectiveness of composite fabrication techniques. Methods, such as pultrusion and filament winding, which use neat resin and fibers benefit from a substantial materials cost reduction over those which utilize prepreg materials. In addition, since these methods generally have lower equipment costs and cycle times, they are able to compete with manual production even without a savings in material costs. There are, however, tradeoffs between cost effectiveness, geometric constraints and quality characteristics for raw material methods. Although pultrusion is the most cost effective method and produces high quality parts, it is limited to constant cross section and unidirectional fiber orientation. Filament winding offers more flexibility in fiber orientation at a higher cost. RTM offers lower cycle times, but the need for fiber forms can increase materials costs and there are limitations on maximum attainable fiber volume fraction.

Unless machine assisted prepreg methods can reduce quality related costs or produce more complex parts, these technologies are only marginally cost effective. This agrees with a recent study [188] which concluded that despite the 6 lb/hr production rates, tape layup equipment was not competitive with automated ply cutting system and manual layup. For simple parts, these methods compete by eliminating the need for compaction between plies and reducing the scrap. Since there is not a large decrease in layup cycle time, it appears that some forms of intermediate automation which increase the efficiency or quality of the manual procedure may be more appropriate. Ink-jet ply location marking/inspection and semi-automated compaction systems have been successfully utilized by Boeing [189] to increase productivity.

Each of the alternative methods reduce the cycle time and therefore the throughput of the system and the work-in-progress inventory costs. For the machine assisted prepreg layup methods, there is a substantial mismatch in the capacities of workstations resulting in a bottleneck at the "slowest" workstation which dominates the response time. Operating below capacity does not offer a competitive edge, since decreases in equipment utilization results in large cost increases and only marginal gains in response time. If process flexibility is desired the emphasis should be placed on developing more balanced equipment lines. Perhaps a more appropriate breakdown of tasks is necessary or less expensive slower equipment in high capacity workstations such as automated cutting. Autoclave capacities which optimize response time are low in comparison to the size of the typical autoclave. The use of individual heated tools would reduce response time by eliminating the wait in the autoclave queue and possibly the labor intensive autoclave preparation and compaction procedures.

Although this study focused on specific methods, many generalizations can be drawn which serve as guidelines for the design of new manufacturing technologies. Since a high level of integration and low assembly costs enable composite structures to successfully compete with other materials, part complexity is an important issue. More complex parts require more manual labor and, therefore, are attractive targets for automation. Much of the equipment technology was borrowed from other industries and does not have the operating characteristics suitable for composites applications. The machine assisted layup methods attempt to imitate complex human motion with complicated computer controlled multi degree of freedom systems. The prepreg material itself was designed primarily to assist manual production and due to its flexible and unpredictable nature is difficult to handle by mechanical devices. These two factors result in high equipment costs and long cycle times. In contrast, raw material methods which simplify the amount of information in the part are able to compete economically. These methods are constrained to a reduced set of geometries in which the part complexity or information content is low resulting in low equipment costs and cycle times.

Equipment design is, therefore, a key area of improvement. There is a strong need for new equipment designed for composites applications which will produce complex geometry parts but will take advantage of the repetitive nature of composite parts. An example of this is the modular design adopted by Airbus [190, 191] for the horizontal stabilizer. The basic module can be repetitively produced by layup robots and special tools to facilitate automation. It was claimed that this method can produce more complex parts at a substantially faster rate than manual fabrication and at the same cost of an equivalent aluminum structure. Perhaps a better solution would be to replace the basic module with a shape that could be economically produced by a form of pultrusion, filament winding or resin transfer molding and use basic shapes to produce more highly integrated structures. Another approach may be to produce the basic microstructure by simplified cost effective methods and then use a forming process to give the part gross geometric complexity. This would be analogous to the stamping of steel parts.

Further research is required to gain a better understanding of raw material processes in order to implement these ideas. The high material costs and level of integration require consistent quality parts. There are several process related issues which restrict the quality of raw material processes. Since the major limitation to pultrusion is fiber orientation, perhaps the fibers could be braided before entering the resin bath to enable production of multidirectional parts. High quality parts could be produced at low cost by filament winding if void formation could be eliminated without the use of autoclave cure. Low viscosity resins and better resin impregnation techniques are necessary to produce parts for markets which require high fiber volume fractions. To produce complex parts, a better understanding of the deformation process is necessary.

The part design process and material selection also play an important role in the automation process. It is important to develop guidelines for engineers to design parts which complement the type of automation available. Customer requirements must be translated into possible economic designs by examining the tradeoffs between cost, quality and system issues using quantitative measures developed in this study. Using currently available technologies, the optimum approach may require the marriage of automated techniques with some form of hand layup. The use of basic materials such as thermoplastics which do not possess some of the inherent disadvantages of thermoset materials is an important area of research. Although cost of thermoplastics is high due to the difficulty in fiber impregnation with high viscosity resins, constant material properties, low cure time and the reversible nature of these materials are beneficial to automation.

References

1 Park, C., "Counting the Costs: New Measures of Manufacturing Performance", *Mechanical Engineering*, January 1987, p 66.

2 Kaplan, R., "Yesterday's Accounting Undermines Production", *Harvard Business Review*, July-August 1984, p 95.

3 Meredith, J. and M. Hill, "Justifying New Manufacturing Systems: A Managerial Approach", *Sloan Management Review*, Summer 1987.

4 Sullivan, W., "Models IEs Can Use To Include Strategic, Non-Monetary Factors in Automation Decisions", *Industrial Engineering*, March 1986, p 42.

5 Meredith, J., "New Justification Approaches for CIM Technologies", *CIM Review*, Spring 1987, p 37.

6 Meredith, J. and M. Hill, Summer 1987.

7 Meredith, J. and N. Suresh, "Justification Techniques for Advanced Manufacturing Technologies", *International Journal of Production Research*, v 24, n 5, 1986, p 1043-1057.

8 Canada, J., "Non-Traditional Method for Evaluating CIM Opportunities Assigns Weights To Intangibles", *Industrial Engineering*, March 1986, p 66.

9 Barr, W., "Risk Analysis Application and Capital Investment Evaluation", 1981 Spring Annual Industrial Engineering Conference Proceedings, p 318.

10 Buck, J., "Risk Analysis Method Can Help Make Firms' Investments Less of A Gamble", *Industrial Engineering*, November 1982, p 198.

11 Sullivan, W. and G. Orr, "Monte Carlo Simulation Analyzes Alternatives in Uncertain Economy", *Industrial Engineering*, November 1982, p 205.

12 Hertz, D., "Risk Analysis in Capital Investment", *Harvard Business Review*, January-February 1964, p 95-106.

13 Kaplan, Robert, "Must CIM be Justified by Faith Alone?", *Harvard Business Review*, March-April 1986.

14 Dhavale, D., "Indirect Costs Take on Greater Importance, Require New Accounting Methods with CIM", *Industrial Engineering*, July 1988, p 42.

15 Schwartz, M. M., *Composites Materials Handbook*, McGraw Hill, 1984.

16 Hoffman, R. E. and D. J. Boll, "The Use of Dynamic Gel Temperatures to Develop Cure Cycles", *29th National SAMPE Symposium Proceedings*, April 1984, p 1411-1421.

17 Thompson, V. and R. Bradley, "Pultrusion of Composite Materials", SME Technical Paper EM76-176, 1976, p 2.

18 *DOD/NASA Structural Composites Fabrication Guide*, Contract Number F33615-79-C-5125, Lockheed Georgia Company, September 1982, p 6-22.

19 Stefanides, E.J. "CNC Machine Slashes Laminated Composites Cost", *Design News*, January 24, 1983, p 136.

20 Schwartz, M. M., 1984, p 4.9.

21 Based on Conversation with Vere Thompson, Boeing Commercial Aircraft, Seattle, WA, June 1985.

22 Sabo, J., "The Filament Winding of Hybrid Composite Driveshafts", 25th National SAMPE Smposium and Exhibition, May 1980, p 481.

23 Country Report, France, The Economic Intelligence Unit, No. 1-1987.

24 Kurtz, M., *Handbook of Engineering Economics*, McGraw Hill, 1984, p 1-117.

25 Based on Conversation with Al Trudeau, Sikorsky Aircraft, Bridgeport, CT, December 1985.

26 Based on Conversation with John Meacham, Northrop Corporation, June 1985.

27 Based on Conversation with Ken Sullivan, Cincinnati Milacron, March 1986.

28 Based on Conversation with Glenn Ewald, Goldsworthy Engineering, March 1986.

29 Based on Conversation with Glenn Ewald, Goldsworthy Engineering, March 1986.

30 Based on Conversation with Jerry Drake, Liquid Control Corporation, September 1986.

31 Based on Conversation with Donald Helmreich, Tyler Machinery, Warsaw, Indiana, October 1987.

32 Based on Conversation with Jerald Janicki, McDonnell Douglas, June 1988.

33 LeBlanc, D.J. et al., *Advanced Composites Cost Estimating Manual*, Volume 1, AFFDL-TR-76-87, Northrop Corporation, Aircraft Division, 1976, p 16.

34 Poggiali, B., *Production Cost Modeling: A Spreadsheet Methodology*, M.S. Study, Department of Materials and Science Engineering, MIT, September 1985, p 55.

35 LeBlanc, D.J. et al., 1976, p 18.

36 "Tape Laying with NC", *American Machinist*, August 1981, p 120-121.

37 Informal Report by Sikorsky on Gerber Activity, 1985.

38 Schwartz, M. M., 19C+, p 433.

39 *DOD/NASA Structural Composites Fabrication Guide*, September 1982, p 3-12.

40 *DOD/NASA Structural Composites Fabrication Guide*, September 1982, p 6-17, 24.

41 Thompson, V. and R. Bradley, 1976, p 7.

42 Conversation with Glenn Ewald, Goldsworthy Engineering, March 1986.

43 Magnamite Graphite Fiber Product Data Sheets, Hercules Incorporated, Wilmington, Delaware.

44 Scheidegger, A., *The Physics of Flow Through Porous Media*, University of Toronto Press, 1974.

45 Conversation with Jerry Drake, Liquid Control Corporation, September 1986.

46 Coulter, J., B. Smith and S. Guceri, "Experimental and Numerical Analysis of Resin Impregnation During the Manufacturing of Composite Materials", Submitted to *Composite Science and Technology*.

47 Ellerbe, G., "RIM Mat Molding - Economic Evaluation of a Structural Composite", 42nd Annual Conference, Composites Institute, SPI, February 1987, Session 3-C.

48 LeBlanc, D. J. et al., 1976.

49 Ostwald, P., *Cost Estimating*, Prentice Hall, Inc. New Jersey, 1984, p 32.

50 Wright, T. P. "Factors Affecting the Cost of Airplanes", *Journal of Aeronautical Engineering*, v 3, n 2, February 1936.

51 Conway, R.W. and A. Schultz, "The Manufacturing Progress Function", *Journal of Industrial Engineering*, January-February 1959, p 39-54.

52 Nadler, G. and W.D. Smith, "Manufacturing Progress Function for Types of Processes", *International Journal of Production Research*, v 2, n 2, 1963, p 115-135.

53 McCampbell, E.W. and C.W. McQueen, "Cost Estimating from the Learning Curve", *Aero Digest*, v 73, p 36.

54 Anderlohr, G. "What Production Breaks Cost", *Industrial Engineering*, September 1969.

55 *Employment Hours and Earnings, United States, 1909-1984, Volume II, Bulletin 1312-12*, U. S. Department of Labor, Bureau of Labor Statistics, March 1985, p 324.

56 Ostwald, P., *Cost Estimating*, Prentice Hall, Inc. New Jersey, 1984, p 47.

57 Based on Conversation with Ed Gerard, Hercules Incorporated, Magna, Utah, March 1986.

58 Dunbar, S., *A Cost Analysis of Composite Prepreg Material*, B. S. Study, Department of Mechanical Engineering, MIT, June 1986.

59 Based on Conversation with Richard Pusch, Woven Structures, Compton, CA 90220, August 1987.

60 Based on Conversation with David Lacey, Composites Reinforcement, Tuscaloosa, Alabama, September 1986.

61 Based on Conversation with Walt Jones, Hercules, Magna, Utah, September 1986.

62 Thompson, V. and R. Bradley, 1976, p 2.

63 Thompson, V. and R. Bradley, 1976, p 2.

64 Busch, J., *Primary Fabrication Methods and Costs in Polymer Processing for Automotive Applications*, M. S. Study, Department of Materials and Engineering, MIT, June 1983, p 35.

65 Price list for Fiberite Toolrite Tooling Materials System, January 1986.

66 Poggiali, B., "Production Cost Modeling: A Spreadsheet Methodology", M.S. Study, Department of Materials Science and Engineering, MIT, September 1985, p 78.

67 Vaccari, J., "New Way to Tool Composites", *American Machinist*, July 1984.

68 Based on Conversation with Glenn Ewald, Goldsworthy Engineering, March 1986.

69 Based on Conversation with Glenn Ewald, Goldsworthy Engineering, March 1986.

70 Busch, J., 1983, p 35.

71 Riddell, R., "RTM - An Update", SAE Technical Paper 830803.

72 Maurer, R. and L. Penn, "A Fresh Look at GRP Resin Injection", 33rd Reinforced Pl[illegible]tics/Composites Conference, SPI, 1978.

73 Klahorst, H [illegible] How to Justify Multimachine Systems", *American Machinist*, September 1983.

74 Meyer, R[illegible]ald, "A Cookbook Approach to Robotics and Automation Justification", Proceedings of Robotics VI Conference, Detroit Michigan.

75 Klahorst, H. T., September 1983.

76 LeBlanc, D. J. et al., 1976.

77 Margolis, J., "Composite Fabricating Economics", *Composites in Manufacturing*, v 4, n 1, 1988.

78 Dunbar, S., June 1986.

79 "Automating Composites Fabrication", *American Machinist and Automated Manufacturing*, November 1987.

80 Kuno, J., "Growth of the Advanced Composites Industry in the 1980's", *31st International SAMPE Symposium Proceedings*, April 1986, p 727-737.

81 McDermott, J., "Assessing the Advanced Composites Market", *Advanced Composites*, April/May 1988, p 52.

82 Reinert, H.S. et al., "AFML Large Aircraft Composite Fuselage Program Process Cost Comparison", 31st SAMPE Symposium, April 1986, Closed Session.

83 "Tape Laying with NC", *American Machinist*, August 1981, p 120.

84 Freeman, W. and B. Stein, "Filament Winding: Waking the Sleeping Giant", *Aerospace America*, October 1985, p 44.

85 English, L., "Automated Composites Fabrication: The Challenge and the Promise", *Materials Engineering*, June 1988.

86 Trends 86: A Survey of the Reinforced Plastics/Composites Industry.

87 Ishikawa, K., *What is Total Quality Control?*, Prentice Hall, 1985.

88 Springer, G.S., "Resin Flow During the Cure of Fiber Reinforced Composites", *Journal of Composite Materials*, v 16, September 1982.

89 Loos, A.C. and G.S. Springer, "Curing of Epoxy Matrix Composites", *Journal of Composite Materials*, v 17, March 1983.

90 Gutowski, T.G., T. Morigaki and Z. Cai, "The Consolidation of Laminate Composites", *Journal of Composite Materials*, v 21, February 1987.

91 Outwater, J., "On the Mechanics of Pultrusion", 41st Annual Conference, RP/C Institute, SPI, January 1986.

92 Han, C. D. and D.S. Lee, "Development of a Mathematical Model for the Pultrusion Process", *Polymer Engineering and Science*, March 1986, v 26, n 6.

93 Batch, G. and C. Macosko, "A Computer Analysis of Temperature and pressure Distributions in a Pultrusion Die", 42nd Annual Conference, RP/C Institute, SPI, February 1987.

94 Aylward, L., C. Douglas and D. Roylance, "A Transient Finite Element Model for Pultrusion Processing", *Polymer Process Engineering*, v 3, n 3, p 247-261, 1985

95 Calius, E. and G. Springer, "Modeling the Filament Winding Process", Fifth International Conference on Composite Materials ICCM-V, 1985.

96 Calius, E. and G. Springer, "Validation of the Filament Winding Process Model", 32nd International SAMPE Symposium, April 1987.

97 Martin, G.Q. and J.S. Son, "Fluid Mechanics of Mold Filling for Fiber Reinforced Plastics", 2nd Conference on Advanced Composite Materials, ASM and ESD, November 1986.

98 Gauvin, R. et al., "The Modeling of Pressure Distribution in Resin Transfer Molding", 41st Annual Conference, RF/C Institute, SPI, January 1986.

99 Gutowski, T.G. and L. Bonhomme, "The Mechanics of Prepreg Conformance", Accepted by *Journal of Composite Materials.*

100 Kershaw, J.A., *SAMPE Quarterly*, v 15, n 13, January 1984.

101 Garnett, G., N. L. Hancox and R.A. Spencer, "A Comparison of the Mechanical Properties of Pultruded and Wet Layup Carbon Fiber Composites", Plastics Institute Conference, London, 1971.

102 "Automated Filament Winding of Thin-Walled Composites", The Composite, McClean Anderson, July 1985, v 4, n 1.

103 Dunbar, S., "Glass Reinforcements for Producing RTM Parts", *Plastics Engineering*, September 1984, p 45.

104 Gonzalez-Romero, V. and C. Macosko, "Design Strategies for Composite Reaction Injection Molding and Resin Transfer Molding", ANTEC 86, p 1292.

105 Magnamite Graphite FIbers Product Data Sheets, Hercules Incorporated, Magna, Utah.

106 Price, H. and S. Cupschalk, "Pulling Force and Its Variation in Composite Materials", *Polymer Blends and Composites in Multiphase Systems*, American Chemical Society, 1984.

107 Garnett, G., N. L. Hancox and R.A. Spencer, "A Comparison of the Mechanical Properties of Pultruded and Wet Layup Carbon Fiber Composites", Plastics Institute Conference, London, 1971.

108 Tessier, N. J. et al., "Ultrasonic Enhancement of Epoxy Matrix Pultrusions", 41st Annual Conference, Reinforced Plastics/Composites Institute, SPI, January 1986.

109 Kruger, H. J., et al., "Filament Winding of Large Graphite Epoxy Cylinders", 25th National SAMPE Symposium and Exhibition, May 6-8, 1980, p 233-242.

110 Based on Conversation with Kurt Adams, Princeton Textile Research Center, August 1987, Magna, Utah, August 1987.

111 Wenz, S. and J. Mijovic, "The Effect of Cure Schedule on Physical/Mechanical Properties of Graphite/Epoxy Composites", *SAMPE Journal*, March/April 1986, p 31.

112 Elegante, T., "Filament Winding", *Mechanical Engineering*, December 1986, p 36.

113 *Product Engineering*, February 1976, p 27. and *Plastics/Design Forum*, March/April 1982, p 54.

114 Meyer, R., *Handbook of Pultrusion Technology*, Chapman and Hall, New York, 1985, p 18-19

115 Mountifield, J. "Forming Processes for Glass Fiber and Resin - Other Methods", *Composites*, September 1969, p 41.

116 Riddell, R., 1983.

117 Thompson, V. and R. Bradley, 1976.

118 LaVerne, L., "Automated Material Deposition: A Putdown for Fabrication Costs", *Advanced Composites*, September/October 1987, p 51-58.

119 Bogas, P., "Why Knitted Reinforcements Are Replacing Woven Roving", *Plastics Technology*, May 1984.

120 "Effect of Weave Distortion on the Physical Properties and Reliability of Composite Structures", Composites Reinforcement Business, Tuscaloosa, Alabama.

121 Birsa, R. and P. Taft, "A New Materials Approach for Providing Transverse Strength in Pultruded Shapes", 39th Reinforced Plastics/Composites Institute, SPI, January 1984.

122 Halpin, J. C., K. Jerine and J. M. Whitney, "The Laminate Analogy for 2 and 3 Dimensional Composite Materials", *Journal of Composite Materials*, v 5, January 1971, p 36.

123 Chan, W. S. and E. Dan-Jumbo, "A Comparison of the Structural Behavior of Laminates Made of Knitted Nonwoven Fabric and Laminates Made of Conventional Unidirectional Tapes", *SAMPE Journal*, November/December 1986, p 21.

124 Macander, A., R. Crane and E. Camponeschi, "Fabrication and Mechanical Properties of Multidimensionally (X-D) Braided Composite Materials", *Composite Materials: Testing and Design (Seventh Conference)*, ASTM STP 893, American Society for Testing and Materials, 1986, p 422-443.

125 Jones, R. M., *Mechanics of Composite Materials*, McGraw Hill, 1976, Section 3.2 and 3.5.

126 Ishikawa, T. and T. Chou, "One Dimensional Micromechanical Analysis of Woven Fabric Composites", *AIAA Journal*, v 21, n 12, p 1714.

127 Ishikawa, T. and T. Chou, "Elastic Behavior of Woven Hybrid Composites", *Journal of Composite Materials*, v 16, January 1982, p 2.

128 Ishikawa, T. and T. Chou, "Stiffness and Strength Behavior of Woven Fabric Composites", *Journal of Materials Science*, v 17, 1982, p 3211-3220.

129 Ishikawa, T. and T. Chou, "One Dimensional Micromechanical Analysis of Woven Fabric Composites", *AIAA Journal*, v 21, n 12, p 1714.

130 Halpin, J. C., K. Jerine and J. M. Whitney, "The Laminate Analogy for 2 and 3 Dimensional Composite Materials", *Journal of Composite Materials*, v 5, January 1971, p 36.

131 Chou, T., "Strength and Failure Behavior of Textile Structural Composites", 1st Technical Conference of American Society for Composite Materials, Dayton, Ohio, 1986.

132 Ma, C., J. Yang and T. Chou, "Elastic Stiffness of Three-Dimensional Braided Textile Structural Composites", ASTM STP 893, American Society for Testing and Materials, 1986, p 404-421.

133 Yang, J., C. Ma and T. Chou, "Fiber Inclination Model of Three-Dimensional Textile Structural Composites", *Journal of Composite Materials*, v 20, September 1986, p 472.

134 Ross, A. L. "Designing with Three-Directional Composites", ASME Paper 74-DE-25.

135 Rosen, B. W., S. N. Chatterjee and J. J. Kibler, "An Analysis Model for A Spatially Oriented Fiber Composites", Composite Materials: Testing and Design, ASTM STP 617, American Society for Testing and Materials, 1977, p 243-254.

136 Ko, F., and C. Pastore, "Structure and Properties of an Integrated 3-D Fabric for Structural Composites", ASTM STP 864, American Society for Testing Materials, 1985, p 428-439.

137 Ko, F., "Tensile Strength and Modulus of a Three-Dimensional Braid Composite", ASTM STP 893, American Society for Testing and Materials, 1986, p 392-403.

138 Piggott, M., *Load Bearing Fibre Composites*, Pergamon Press, Section 4.3.4.

139 Chan, W. S. and E. Dan-Jumbo, November/December 1986, p 21.

140 Ross, A. L. "Designing with Three-Directional Composites", ASME Paper 74-DE-25.

141 Kardos, J.L., M.P. Dudukovic and R. Dave, "Void Growth and Resin Transport During Processing of Thermosetting Matrix Composites", *Advances in Polymer Sciences*, v 80, 1986, p 101.

142 Kardos, J.L. et al., "Void Formation and Transport During Composite Laminate Processing: An Initial Model Framework", ASTM STP 797, 1983, p 96-109.

143 Wenz, S. and J. Mijovic, "The Effect of Cure Schedule on Physical/Mechanical Properties of Graphite/Epoxy Composites", *SAMPE Journal*, March/April 1986, p 31.

144 Hancox, N. L. "The Effects of Flaws and Voids on the Shear Properties of CFRP", *Journal of Materials Science*, v 12, 1977, p 884-892.

145 Hancox, N. L. "The Influence of Voids on the Hydrothermal Response of Carbon Fiber Reinforced Plastics", *Journal of Materials Science*, v 16, 1981, p 627-632.

146 Campbell, F.C., A.R. Mallow, F.R. Muncaster, B.L. Boman, G.A. Blase, "Computer-Aided Curing of Composites", AFWAL-TR-86-4060, July 1986.

147 Bascom, W., "Some Surface Chemical Aspects of Glass-Resin Composites Part I: Wetting Behavior of Epoxy Resins on Glass Filaments", SPE, 1965, Section 15-B.

148 Elegante, T., December 1986, p 36.

149 Kruger, H. J., R. C. Curley, V.L. Freeman, "Filament Winding of Large Epoxy Cylinders", 25th National SAMPE Symposium, May 1980, p 233.

150 Tessier, N. J., et al., 1986.

151 Macander, A., R. Crane and E. Camponeschi, 1986, p 422-443.

152 Judd, N.C.W. and W.W. Wright, "Voids and Their Effects on the Mechanical Properties of Composites - An Appraisal", *SAMPE Journal*, January/February 1978, p 10.

153 Yoshida, H., T. Ogasa and R. Hayashi, "Statistical Approach to the Relationship between ILSS and Void Content", *Composites and Science Technology*, v 25, 1986, p 3-18.

154 Hancox, N. L., "The Influence of Voids on the Hydrothermal Response of carbon Fiber Reinforced Plastics", *Journal of Material Science*, v 16, 1981, p 627-632.

155 Harper, B. D., G. H. Staab and R. S. Chen, "A Note on the Effects of Voids Upon the Hygral and Mechanical Properties of AS4/3502 Graphite/Epoxy", *Journal of Composite Materials*, v 21, March 1987, p 280.

156 Johnson, W. and S. Ghosh, "Some Physical Defects Arising in Composite Fabrication", *Journal of Material Science*, v 16, 1981, p 285-301.

157 Tsai, W., "Effects of Porosity on Delamination of Resin-Matrix Composites", MIT Ph.D. Proposal, Department of Materials Science and Engineering, May 1986.

158 Elegante, T., 1986.

159 Chamis, C. C., "Simplified Composite Micromechanics Equations for Strength, Fracture Toughness and Environmental Effects", 39th Annual Conference, RP/CI, SPI, January 1984, Session II-D, p 9.

160 Magnamite Graphite Fibers product Data Sheets, Hercules Incorporated, Magna, Utah.

161 Technical Bulletin for Shell Chemical Company, SC:828-86R and SC:712-86.

162 Taguchi, G., *Introduction to Quality Engineering*, Asian Productivity Organization, 1986.

163 Ayres, R., "Complexity, Reliability and Design: Manufacturing Implications", *Manufacturing Review*, v 1, n 1, March 1988.

164 Margolis, J., "Composite Fabricating Economics", *Composites in Manufacturing*, v 4, n 1.

165 Meister, D., *Behavioral Foundation of System Development*, Wiley, New York, 1976.

166 Gutowski, T.G. et al., February 1987.

167 Lee, W. et al.,"Heat of Reaction, Degree of Cure and Viscosity of Hercules 3501-6 Resin", *Journal of Composite Materials*, v 16, 1982, p 510.

168 Kardos, J.L., M.P. Dudukovic and R. Dave, "Void Growth and Resin Transport During Processing of Thermosetting Matrix Composites", *Advances in Polymer Sciences*, v 80, 1986, p 101.

169 Grayson, M. A. and C. J. Wolf, *Advances in Chemistry Series*, J. Koenig editor, ACS, v 174, 1979, p 53.

170 Grayson, M. A., ACS Symposium Series, n 132, ACS, 1980, p 449.

171 Brand, R. A., Brown, G. G. and McKague, E. L., "Processing Science Epoxy Resin Composites", AFWAL-TR-83-4124, January 1984, p 169-175.

172 Kingery, W. D., *Introduction to Ceramics*, Wiley, New York, 1960, Chapter 10, p 291.

173 Dave, R., J. L. Kardos, S. J. Choi and M. K. Dudukovic, "Autoclave vs. Non-Autoclave Composite Processing", 32nd International SAMPE Symposium, April 1987, p 325.

174 Yokota, M., "In-Process Controlled Curing of Resin Matrix Composites", *SAMPE Journal*, July/August 1978, p 11.

175 Maurer, R. and L. Penn, 1978.

176 Rogowski, A. H., "Compression Molding Simulation Design of Complex Geometry Composite Parts", MIT M.S. Study in Mechanical Engineering, June 1987, p 48.

177 Martin, G. Q. and J.S. Son, "Fluid Mechanics of Mold Filling for Fiber Reinforced Plastics", 2nd Conference on Advanced Composite Materials, American Society of Metals and Engineering Society of Detroit, Nov 1986, p 149.

178 Gauvin, R., M. Chibani and Lafontaine, "The Modeling of Pressure Distribution in Resin Transfer Molding", 41st Annual Conference for Reinforced Plastics/Composites Institute, SPI, January 1986, Session 19-b.

179 Coulter, J., B. Smith and S. Guceri, "Experimental and Numerical Analysis of Resin Impregnation During the Manufacturing of Composite Materials", Submitted to *Composites Science and Technology.*

180 Based on Conversation with Kurt Adams, Princeton Textile Research Center, August 1987.

181 Adams, K., B. Miller and L. Rebenfeld, "Forced In-Plane Flow of an Epoxy Resin in Fibrous Networks", *Polymer Engineering and Science*, mid-November 1986, v 26, n 20, p 1434.

182 Williams, J.G., C.E.M. Morris and B.C. Ennis, "Liquid Flow Through Aligned Fiber Beds", *Polymer Engineering and Science*, June 1974, v 14, n 6, p 413.

183 Carman, P. C., *Transactions of Institute of Chemical Engineering*, v 15, p 150, 1937.

184 Williams, J.G., C.E.M. Morris and B.C. Ennis, "Liquid Flow Through Aligned Fiber Beds", *Polymer Engineering and Science*, June 1974, v 14, n 6, p 413.

185 Martin, G.Q. and J.S. Son, "Fluid Mechanics of Mold Filling for Fiber Reinforced Plastics", 2nd Conference on Advanced Composite Materials, American Society of Metals and Engineering Society of Detroit, Nov 1986, p 149.

186 Vaccarella, P., "The Fabrication of FRP Chemical Resistant Equipment by the Resin Transfer Technique", 34th Annual Technical Conference, Reinforced Plastics/Composites Institute, SPI, 1979.

187 Technical Bulletin for Shell Chemical Company, SC:828-86R.

188 "Automating Composites Fabrication", *American Machinist and Automated Manufacturing*, November 1987.

189 McLane, R., "Economic Issues in Composites Manufacturing", Proceedings of the American Society for Composites, September 1988, p 23.

190 Sarh, B., "Robotic Applications to Automated Composite Aircraft Component Manufacturing", SME Technical Paper, MF85-506, 1985.

191 Sarh, B., "Principle Tests for the Automated Production of the Airbus Fin Assembly with Fiber Composite Materials", 29th National SAMPE Symposium and Exhibition, April 1984.

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STUDY OF THE APPLICATION OF AUTOMATION TO COMPOSITES MANUFACTURE

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Key Words

Composites
Manufacturing
Automation
Resin transfer molding
Pultrusion
Filament Winding

Economic Analysis

Several alternative manufacturing technologies have been developed to replace current labor intensive manual fabrication methods for advanced thermoset composites. The objective of this study was to evaluate the effect of direct labor savings, quality improvements and process flexibility on manufacturing cost and to identify desirable characteristics for new equipment. To estimate the cost benefits of replacing manual laborers with equipment, an economic model based on data from the literature and industry was developed. Knowledge of process physics and human error models was used to assess overall quality and estimate related costs such as rework, inspection and scrap. To evaluate process flexibility, system simulation techniques were used to analyze the tradeoffs between response time, work-in-progress inventory, equipment utilization and manufacturing cost.

U.S. Army Materials Technology Laboratory
Watertown, Massachusetts 02172-0001
STUDY OF THE APPLICATION OF AUTOMATION TO COMPOSITES MANUFACTURE

Susan M. Krolewski
Massachusetts Institute of Technology
Cambridge, MA. 02139

Technical Report MTL TR 89-47, May 1989
114 pp-illus.-tables, Contract DAAG46-85-K-0001
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